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STELLINGEN

behorende bij het proefschrift

**'Mechanical force and
subcutaneous tissue discolouration in potato'**

**Geert-Jan Molema
Wageningen, 30 november 1999**

1. Zelfs laag-energetische botsingen leiden tot onderhuidse beschadiging indien aardappelknollen herhaaldelijk op dezelfde plek worden geraakt.
Dit proefschrift
2. Ondanks verschil in gedrag tussen een aardappelknol en een elektronische meetbol is de meetbol een nuttig instrument om inzicht te krijgen in de krachten die een knol bij bewerking ondergaat.
Dit proefschrift
3. De (lijdens)weg die consumptieaardappelen afleggen tussen veld en tafel, is vaak onnodig lang.
Dit proefschrift
4. De relatie tussen de duur van de bewaring en de intensiteit van de onderhuidse weefselverkleuring bij aardappelknollen is minder eenduidig dan algemeen wordt aangenomen.
Dit proefschrift
5. Genetische modificatie, leidend tot het niet optreden van onderhuidse weefselverkleuring na mechanische overbelasting van de aardappel, lost het probleem van kwaliteitsverlies slechts gedeeltelijk op.
6. Het gebrek aan een heldere en consistente terminologie belemmert een effectieve communicatie over mechanische beschadiging van aardappelknollen.
7. De mechanische belasting waarboven aardappelknollen beschadiging oplopen is niet bekend. Indien deze wel bekend zou zijn, is de praktische benutting van deze kennis nog zeer gecompliceerd.
8. De traditionele grondbewerkingen in de akkerbouw na de oogst, verdienen zichzelf terug.
9. Om de grote hoeveelheid informatie over de relatie tussen mechanische beschadiging en onderhuidse weefselschade beter te benutten, is een financiële beloning voor een beter eindproduct gewenst.
10. Mensen zijn, evenals aardappelen, blauwgevoelig.

**Mechanical force and
subcutaneous tissue discolouration in potato**

Geert-Jan Molema

Promotor: dr. ir. P.C. Struik
Hoogleraar in de gewasfysiologie

Co-promotor: dr. ir. H. Breteler
Senior wetenschappelijk onderzoeker IMAG

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Mechanical force and subcutaneous tissue discolouration in potato

Geert-Jan Molema

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ABSTRACT

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Over the last decades rapid developments in potato production and mechanization occurred, aiming to increase capacity and to reduce costs. Concomitantly, potatoes can be damaged more easily. Subcutaneous tissue discolouration, a major quality problem, is a result of mechanical damage and reduces the market value of potatoes considerably. This study focused on the effect of mechanical force on subcutaneous tissue discolouration.

The study started with an analysis of representative Dutch ware-potato handling-chains in terms of utilization, produce-friendliness and the subsequent incidence of subcutaneous tissue discolouration. In parallel, forces acting in these chains were quantified. Using an instrumented sphere (IS100) a better understanding of the forces acting in the chain was obtained. It appeared that 78% of the measured impacts occurred during packaging and that 98% of the impacts did not exceed 150 g. The results of the chain analysis were the basis for experiments on dose-effect relations, focused on the effect of repetitive impacts and impact body shape on the occurrence of subcutaneous tissue discolouration. A new computer-controlled pendulum was developed to impact potato tubers at a desired rate. This pendulum proved to be an adequate tool to impact tubers precisely and reproducibly. In particular the effect of repetitive impacts on potato tubers and the effect of the shape (curvature) of both potato and impact body became clear. It appeared that splitting 0.6 J of impact energy over 9 equal impacts reduced the depth and volume of discoloured tissue by 33 and 64%, respectively. Spherical impact bodies, relative to a non-spherical one, doubled the volume and depth of discoloured tissue.

The results urge a reappraisal of some commonly accepted insights. For example the effect of low-energetic repetitive impacts on subcutaneous tissue discolouration cannot be neglected. The use of spherical impact bodies has to be minimized.

The research suggests important routes for the potato sector to make adequate changes in technique and technology. These changes make it possible to reduce both the number and the intensity of impacts and should result in a produce which can be offered to the consumer in a condition (almost) free of subcutaneous tissue discolouration. When the utilization of machinery is optimized damage reduction may be substantial. Some potential improvements are: better utilization of machinery, better planning of bunker storage, box handling and improved temperature control of the tubers.

To further optimize the whole potato handling-chain with respect to produce-friendliness additional research should focus on fundamental knowledge that is currently missing, and on developing an optimal logistic handling concept. Crucial in this concept are flexibility and produce-friendliness. Ideally, potatoes may be transported along different routes and the number and intensity of impacts are minimal. Also repetitive impacts on the same tuber site and the use of spherical impact bodies are avoided. The effect of the time interval between consecutive impacts has to be studied. It should also be elucidated at which curvature spherical impact bodies cause damage.

To create a more produce-friendly attitude of growers, and other actors in the potato handling-chain a better differentiation between 'good' and 'poor quality' potatoes is necessary. A financial incentive could have a substantial effect, resulting into potatoes with a high quality, *i.e.* free of tissue discolouration.

Keywords: blackspot, bruising, chain, handling, impact, instrumented sphere, internal damage, mechanical force, pendulum, potato, *Solanum tuberosum* L., subcutaneous tissue discolouration

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Dit proefschrift draag ik op aan mijn vader Hendrik Folkert (Henk) Molema
(overleden op 13 maart 1998)

WOORD VOORAF

Na een boeiende periode van opzetten, uitvoeren en beschrijven van onderzoek over onderhuidse weefselbeschadiging in aardappelen ligt het resultaat voor u. Het proefschrift is af! Aanvankelijk was een promotieonderzoek niet het uitgangspunt. Het in 1993/1994 in opdracht van de toenmalige Nederlandse Aardappel Associatie (NAA), onder projectleiderschap van ir. A. Bouman, uitgevoerde ketenonderzoek aardappelen bracht hierin verandering. In dit project werd nader onderzocht waar in de keten onderhuidse weefselbeschadiging wordt veroorzaakt en in welke mate. Het onderzoek leverde zoveel vragen voor vervolgonderzoek op dat het toenmalige hoofdafdelingshoofd dr. ir. F.G.J. Tijink voorstelde er een promotieonderzoek van te maken. Al gauw volgden hierover gesprekken met de beoogde promotor prof. dr. ir. P.C. Struik.

Het promotieonderzoek werd officieel gestart eind 1994 met als promotor prof. dr. ir. P.C. Struik (hoogleraar in de gewasfysiologie) en co-promotor dr. ir. H. Breteler (toenmalig hoofd van de hoofdafdeling Agrotechniek). Aansluitend werd een begeleidingscommissie geformeerd bestaande uit voornoemde personen, ing. A.H. Bosma (toenmalig hoofd afdeling Oogst en Handling) en ir. E.H. Woltjer (toenmalig directeur Agrico Research Emmeloord). De plaats van ing. A.H. Bosma werd in 1999 overgenomen door dr. ir. C. Lokhorst (clusterleider Teelttechnologie en Ketens). De commissie begeleidde het project op hoofdlijnen en fungeerde daarbij als klankbord. In een later stadium richtte de commissie zich meer op het kritisch beoordelen van manuscripten, meestal bestemd voor publicatie in een wetenschappelijk tijdschrift.

Dit proefschrift is het product van een buitengewoon prettige samenwerking van vele mensen die samen het projectteam vormden. In de loop der tijd zijn diverse wijzigingen in de personele bezetting opgetreden, desalniettemin was er gedurende het hele traject een vaste kern van mensen van zowel IMAG te Wageningen als van het IMAG-proefbedrijf 'Oostwaardhoeve' te Slootdorp.

Op deze plaats wil ik graag de mensen bedanken die betrokken waren bij het onderzoek en het tot stand komen van dit proefschrift. De initiator van dit onderzoek, ir. A. Bouman, wil ik hartelijk danken voor zijn initiatief en het creëren van een stimulerende werksfeer. Financieel werd het onderzoek mogelijk gemaakt door enerzijds een bijdrage van de toenmalige Nederlandse Aardappel Associatie (NAA) en anderzijds door programmafinanciering (programma 198: Technologie voor duurzame open teelten) van het Ministerie van Landbouw, Natuurbeheer en Visserij (LNV). Het probleeminventariserende deel van het onderzoek, waaraan de NAA een bijdrage leverde, werd begeleid door een hiervoor ingestelde commissie bestaande uit de heren ir. C.D. van Loon (NAA), mr. R. van Diepen (toenmalige Vereniging ter Behartiging van den Nederlandschen Aardappelhandel, VBNA), G. Overheul (aardappelteler), A. Vente (toenmalig directeur Nedato) en ir. A. Bouman (projectleider). Begeleidingscommissie nogmaals bedankt!

In het probleeminventariserende deel van het onderzoek is medewerking verleend

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Van grote betekenis voor dit onderzoek was ook ing. J.J. Klooster. Jan, met jou heb ik heel wat ritjes gemaakt om het praktische deel van het onderzoek uit te voeren. Hiervoor werd door een groot deel van het land gereisd. De vertrektijd 's morgens was je nooit te vroeg en dit maakte het mogelijk om zeer efficiënt te werken. Van groot belang waren jouw kritische houding en advies ten aanzien van de afbakening van het promotieonderzoek. Jouw ervaring hiermee bleek van essentieel belang. Verder wil ik ing. R. Sprong bedanken voor zijn inzet op die momenten dat extra menskracht nodig was.

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geleverde bijdrage aan de ontwikkeling van het pendulum, welk cruciaal was bij de uitvoering van het verklarende deel van het onderzoek.

Een grote bijdrage is ook geleverd door medewerkers van het IMAG-proefbedrijf 'Oostwaardhoeve' onder leiding van de heren P.J. Goedbloed en ing. C. Sonneveld. Peter en Cor, bedankt voor de prettige samenwerking. Daarnaast ben ik veel dank verschuldigd aan de medewerkers G.J. Ramaker, M.J. Lawerman, T. Koudenburg, H. Noppe, G.K. Haverkamp en alle anderen die tussendoor hand- en spandiensten verleenden. Het beschikbaar maken van een grote hoeveelheid puntgave (beschadigingsvrije) aardappelen met dezelfde oorsprong gedurende een periode van 7 maanden voor de verklarende experimenten is uniek en van grote waarde geweest voor dit onderzoek.

Om tot verantwoorde conclusies en uitspraken te kunnen komen was een goede statistische onderbouwing onontbeerlijk. Ik wil hierbij J.V. van den Berg en dr. M.M.W.B. Hendriks danken voor hun intensieve begeleiding bij zowel de opzet van de proeven als de uiteindelijke analyse van de gegevens. Verder wil ik S.F. van Heulen bedanken voor de audiovisuele ondersteuning. Tot slot wil ik graag nog een keer mijn dank uitspreken aan Ben Verwijs die ook de lay-out van dit proefschrift voor een groot deel heeft verzorgd.

Graag sluit ik af met het uitspreken van de hoop dat de sector baat mag hebben bij de resultaten beschreven in dit proefschrift en dat er nu reeds voldoende aanknopingspunten zijn voor een verbetering van het productvriendelijk bewerken van aardappelen. Tevens hoop ik in de gelegenheid te worden gesteld de aan de orde gestelde problematiek verder te mogen doorgronden en missende kennis te genereren waardoor uiteindelijk de mogelijkheid wordt geboden om een optimale bewerkingsketen te realiseren. Ik wens een ieder die dit proefschrift of een gedeelte ervan leest veel leesplezier en daag u hierbij tevens uit tot het doen van suggesties ten aanzien van toekomstige onderzoek.

Geert-Jan

ACCOUNT

Parts of this thesis have been or will be published in international scientific journals:

- Chapter 2 Molema, G.J., A. Bouman, B.R. Verwijs, J.V. Van Den Berg & J.J. Klooster, 1999. Subcutaneous tissue discolouration in ware-potatoes. 1. A chain analysis in the Netherlands. *Potato Research*, accepted.
- Chapter 3 Molema, G.J., P.C. Struik, B.R. Verwijs, A. Bouman & J.J. Klooster, 1999. Subcutaneous tissue discolouration in ware-potatoes. 2. Impact measured by an instrumented sphere. *Potato Research*, accepted.
- Chapter 4 Molema, G.J., B.R. Verwijs, L. Oudshoorn & P.C.M. Wennekes. A computer-controlled pendulum to impact potato tubers precisely, submitted.
- Chapter 5 Molema, G.J., B.R. Verwijs, J.V. Van Den Berg & H. Breteler, 1997. Effect of repetitive impacts on subcutaneous tissue discolouration in potato tubers. *Netherlands Journal of Agricultural Science* 45: 185-198.
- Chapter 6 Molema, G.J., J.J. Klooster, B.R. Verwijs, M.M.W.B. Hendriks & H. Breteler, 1997. Effect of impact body shape on subcutaneous tissue discolouration in potato tubers. *Netherlands Journal of Agricultural Science* 45: 407-421.

For this thesis the text of published or submitted articles was integrally adopted. Editorial changes were made for reasons of uniform presentation.

Reference should be made to the original article(s).

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CHAPTER 1

General introduction

Trends in potato production

Dutch ware-potatoes and their importance

Potato (*Solanum tuberosum* L.) is a very important crop, which significantly contributes to the human food supply all over the world (18,381,000 ha corresponding to 295,118,000 tonnes, averaged over the period 1995-1997; Struik & Wiersema, 1999). From 1995 to 1998 the average area of potatoes in the Netherlands was *ca* 180,000 hectares (CBS/LEI-DLO, 1999), which is *ca* 22% of the area under arable crop production. The annual average total production (1995-1997) was 7.8 million tonnes (CBS/LEI-DLO, 1999). Of the total potato crop area, *ca* 45% (CBS/LEI-DLO, 1999) was used for ware-potatoes for the fresh or processing market. Almost 90% of the fresh ware-potatoes is pre-packed (Anonymous, 1998). In the Netherlands the most important distribution channel for fresh potatoes is the supermarket, which in 1997 sold 73% of all the fresh potatoes. The Dutch potato consumption is 85 kg (fresh weight) per caput per year of which 53 kg as peeled and unpeeled fresh potatoes and 32 kg as processed potatoes. The gross production value of potatoes is *ca* 1 billion Euro of which *ca* 70% is exported (CBS/LEI-DLO, 1999).

Chain mechanization and automation

To reduce costs, to minimize labour requirement and to increase efficiency rapid developments in potato production and mechanization took place during recent decades. Many processes are highly mechanized and sometimes automated (see Figure 1.1) and the capacity of machinery is increased. Consequently labour demand per tonne of potato has decreased.

A negative consequence of the rapid developments in mechanization and the subsequent increasing capacities in production is that potatoes can be damaged more easily.

Damage and economic impact

Damage to agricultural produce may appear in greatly different forms. Potato tuber damage can be divided into external and internal damage (Chowdhury *et al.*, 1990). The type of damage depends on the physical and biological parameters of the produce and on the type of load (Sitkei, 1986). Damage is often induced by static or dynamic external forces, or by internal forces. Sitkei (1986) stated that damage resulting from

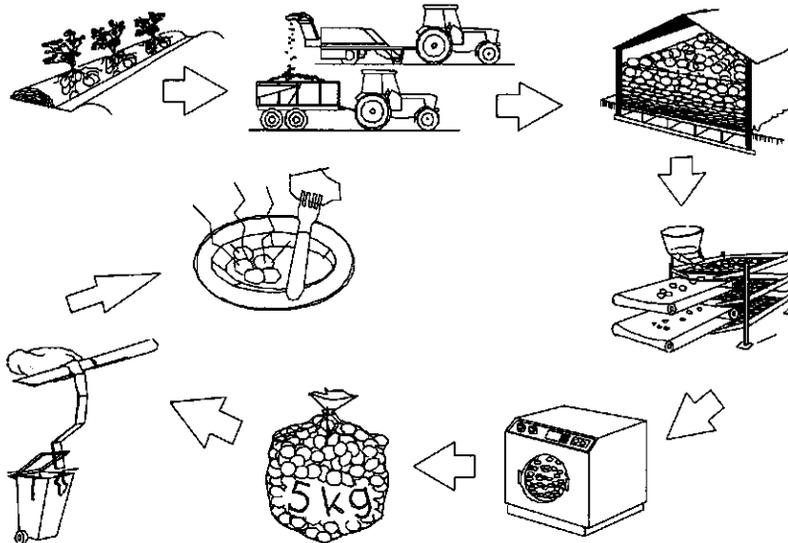


Figure 1.1. Schematic representation of a modern Dutch ware-potato handling-chain.

internal forces is caused by physical variation inside a produce, for example variation of the temperature and moisture content, or by chemical and biological variation. The phenomenon of impact due to mechanical force occurs frequently during handling, transport and treatment of bulk agricultural produce (Sitkei, 1986). Nelson & Mohsenin (1968) stated that bruising (subcutaneous tissue damage, see section on *Mechanical impact and subcutaneous tissue discolouration*) occurs in every step of the harvest and handling operations.

Due to technological progress the frequency of external injuries is decreasing. Nowadays, internal injuries become increasingly important. A major quality problem is subcutaneous tissue discolouration as a consequence of mechanical impact. The discolouration resulting from an impact can usually only be observed after peeling. Subcutaneous tissue discolouration reduces both quality and quantity of marketable potatoes and therefore causes substantial economic damage in the potato industry worldwide.

Harris (1992) and Peters (1996) reported mechanical damage as one of the most important causes of direct and indirect loss of potato in the world. Harris (1992) stated that avoidance of mechanical damage would make the most significant single contribution to increase productivity. It has been estimated that on average more than 20% of the crop in the UK sustains largely avoidable damage at harvest (Harris, 1992). The British Potato Marketing Board estimated the losses caused by mechanical potato damage at £30 million, corresponding to approximately £200 per hectare (Anonymous, 1994). On a total potato production in the USA of \$2,000 million, Preston & Glynn

(1995) reported losses of at least \$125 million (*ca* 6%), on the way from the potato field to the consumer. Brook (1996) reported costs of damage ('bruising') in the USA of *ca* \$300 million and described this figure as a conservative estimate of what would be gained on an annual average if mechanical damage could be eliminated. In the Netherlands *ca* 1.3% of the ware-potato fresh weight is not marketable, corresponding to a financial loss of *ca* 2.6% (E.H. Woltjer, pers. comm.). A multiple of these figures is lost by damage.

Scientific background

Tissue properties and damage

Agricultural produce is active, biological material, of which composition, moisture content and texture vary continuously during growth, ripening and storage. During development the texture strongly responds to factors such as humidity, temperature, supply of oxygen and nutrients (Sitkei, 1986). The mechanical properties are also influenced by genetic factors.

Agricultural produce is visco-elastic (Mohsenin, 1986). From the limited data available it appears that the visco-elastic behaviour is non-linear during exposure to impact; the ratio of stress to strain depends on duration and magnitude of stress.

Impact of tissue can cause cell-rupture (Mathew & Hyde, 1992) within a small volume of a cellular system (Sitkei, 1986) at the 'biological yield point'. The term biological yield point is commonly used to identify the point beyond which the stress results in cell-disruption in biological materials. The biological yield point is the point on the force (stress)-deformation curve at which the relation between force and deformation deviates from linearity. The sensitivity to damage of produce is determined by the biological yield point to a major degree. If the load, a produce is exposed to, does not reach the biological yield point, the cellular system will not be disrupted, and severe quality loss of the produce will not occur (Sitkei, 1986). However, by repetitive impacts, the biological yield point may be reached or exceeded even if each load is below the biological yield point. The reason is that many materials soften under repeated loads and their strength decreases (Sitkei, 1986).

If cell wall extension during impact is considered to be simply a physical process, the mechanical properties of the cell walls are governing the rate of extension. Van Es (1975) reported that the elasticity of the wall, the wall thickness, the cell dimensions, the stress before impact and the nature of the cell content are important factors determining the deformation of the tissue during impact.

Goldsmith (1960) defined impact as a collision between two bodies whereby large forces are applied and removed in a very short time (see Figure 1.2). As a consequence stress waves will develop and travel away from the point of impact. Around the point of impact a deformation and stress zone are produced.

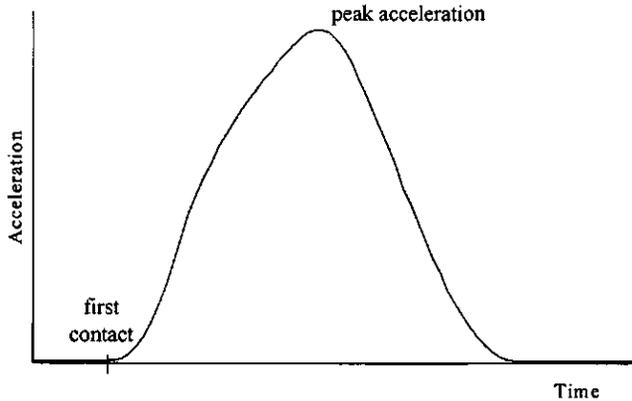


Figure 1.2. Simplified representation of an acceleration-time curve during a collision.

According to Bowden & Tabor (1954) four phases can be distinguished during impact:

- 1: Initial elastic deformation during which the region of contact will be deformed elastically and will recover fully without residual deformation;
- 2: Onset of plastic deformation, the resulting deformation will not be fully recovered;
- 3: Full plastic deformation during which the deformation continues from elastic-plastic to fully plastic;
- 4: Elastic rebound during which a release of elastic stress takes place.

For each produce, the different phases result from various levels and types of mechanical force. Both mechanical force and produce properties determine the phase attained and thereby the resulting damage.

Mechanical impact and subcutaneous tissue discolouration

Subcutaneous tissue discolouration, bruising, blackspot, tissue damage and other terms, though usually poorly defined, are often used to describe approximately the same phenomenon. Among the different types of mechanical damage subcutaneous tissue discolouration needs the least amount of energy to occur, so its presence can be taken as a criterion for design or adjustment of potato machinery (Baheri, 1997) and potato chains.

Exposure of potatoes to mechanical impact may induce subcutaneous tissue damage. Consequently dark patches may develop under the intact skin at the site of impact (Stevens & Davelaar, 1996). Subcutaneous tissue discolouration develops in one to three days after impact (Mathew & Hyde, 1992). Mostly the discoloured tissue is located in the region of the vascular ring (Meijers, 1987; see Figure 1.3). In this

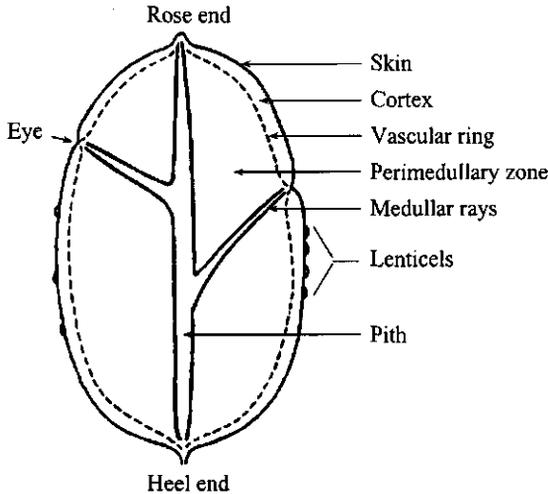


Figure 1.3. Anatomy of the potato tuber (after Rastovski *et al.*, 1987).

thesis tissue discolouration encompasses all blue and blue-grey deviation in tissue colour relative to the surrounding tissue. In referring to literature we have substituted the different terms used for subcutaneous tissue damage by subcutaneous tissue discolouration where and as much as considered allowable.

Subcutaneous tissue discolouration is an internal discolouration of tuber tissue caused by a sequence of biochemical oxidations initiated by mechanical injury (Stevens & Davelaar, 1997). The key enzyme in blackspot formation is polyphenol oxidase (PPO), as has been proven by means of antisense inhibition of PPO gene expression (Bachem *et al.*, 1994; see also Figure 1.4).

The susceptibility of potatoes to the occurrence of subcutaneous tissue damage and subsequent subcutaneous tissue discolouration varies between cultivars and is positively related to tuber properties as low potassium content, high maturity, low turgor pressure, low temperature, high dry matter content, large tuber size and small radius of curvature of the tuber (Brook, 1996). Investigations have shown a direct positive relationship between the susceptibility to tissue discolouration and the specific gravity (*e.g.* Van Es, 1975). However, there are differences between cultivars and between tubers of the same cultivar. Also impact properties as high dose of absorbed impact energy and high impact velocity enhance the occurrence of subcutaneous tissue discolouration (Brook, 1996).

Variation in tuber temperature accounted for about half the variation in resistance to subcutaneous tissue discolouration (Johnson & Wilson, 1969) and about half of the observed susceptibility to tissue discolouration (Peterson & Hall, 1974). Susceptibility to tissue discolouration is also influenced by storage factors such as pile height.

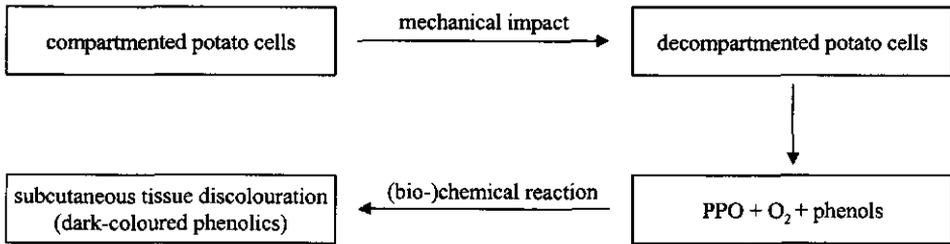


Figure 1.4. Schematic representation of a pathway of tissue discoloration in potato (after Stevens *et al.*, 1998).

Knowing the relative importance of all these factors would help to determine how to use resources to minimize subcutaneous tissue discoloration. Brook (1996) stated that equipment designers need to know which drop heights and impact surface shapes tubers can tolerate at various levels of susceptibility to subcutaneous tissue discoloration. Also the effect of cushioning of impact areas on tissue discoloration needs to be known.

Approaches in damage reduction

Sitkei (1986) reported the following possibilities for reduction of subcutaneous tissue discoloration:

- designing the elements of the machine performing an operation in such a way that the forces acting on the material are the lowest possible;
- carrying out harvesting or manipulation operations when the state of the produce is such that its mechanical strength is sufficient to render the produce less sensitive to subcutaneous tissue discoloration, and
- breeding species of improved quality, which are able to support relatively great loads without suffering subcutaneous tissue discoloration.

Peters (1996) attached great hopes to genetic engineering in terms of breeding varieties less susceptible to damage. This technique could yield new cultivars that better withstand the mechanical forces during mechanical handling (Mohseni, 1986).

Problem definition and objectives

During the last century considerable research efforts have been dedicated to subcutaneous tissue discoloration, resulting in several practical recommendations with respect to breeding and handling. However, current information shows that

although progress has been made, there is still a need for further research so that potatoes can be offered to the consumer in a condition free of damage (Peters, 1996). The main approaches have been to reduce or totally prevent exposure to mechanical force and to produce more resistant potatoes (Peters, 1996). Despite the available results every year subcutaneous tissue discolouration causes significant economic damage. Reduction in pigment formation by genetic engineering does not provide an integral solution for the problem of subcutaneous tissue damage. The stage of cell decompartmentation and concomitant tissue dehydration may remain unaffected and the quality will be lowered. Stevens *et al.* (1998) stated that suppression of the decompartmentation process would therefore be a better approach.

Peters (1996) concluded that the avoidance of mechanical injuries by the use of new technology currently represents the most promising method for preventing tuber damage. For the short-term the largest effect can be expected from optimizing the construction and utilization of handling equipment, attempting to minimize the number and intensity of impacts. So, for improvement on the short-term, research has to focus on the relationship between impact and subcutaneous tissue discolouration.

From which links in the Dutch ware-potato handling-chain subcutaneous tissue discolouration originates and how much each link contributes to the overall damage is not known. To elucidate the relationship between damage and the characteristics of the chain it is essential to evaluate the construction and utilization of Dutch chains. Moreover, the number and intensity of impacts are not known and need to be investigated in an effort to establish clear relationships between impact and damage.

The effect of different types of impacts, *e.g.* related to impact body shape, and the effect of a sequence of impacts at the same site of the tuber on subcutaneous tissue damage are also not known. To study dose-effect relations a precise and reproducible method is needed to simulate the range of impacts potatoes undergo in practice.

The research described here aimed to study the effect of mechanical impact on subcutaneous tissue discolouration. The research started with an analysis of the handling-chain in terms of utilization, produce-friendliness and the subsequent accumulation of subcutaneous tissue discolouration. In parallel forces acting in this chain were quantified. The knowledge obtained was the basis for experiments on dose-effect relations, focused on the effect of repetitive impacts and impact body shape on subcutaneous tissue discolouration.

The following questions were addressed:

- What are the characteristics of representative Dutch ware-potato handling-chains in terms of transportation distance, number and type of drops, drop heights, transportation speeds, changes in speed and direction of transportation?
- From which links in the handling-chain does subcutaneous tissue discolouration originate and to what extent?
- What is the number and intensity of impacts in different phases of representative

Chapter 1

Dutch ware-potato handling-chains?

- To which drop height onto a defined surface do the measured impacts correspond?
- What is the relation between the number of impacts and subsequent subcutaneous tissue discolouration?
- How can impacts that potatoes undergo in practice best be simulated accurately and reproducibly?
- 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?
- What is the relationship between the number of impacts and the volume and depth of discoloured tissue?
- 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?
- 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 any interaction between impact energy level and impact body shape in relation to the volume and depth of discoloured tissue?

Delimitation

To keep the research project manageable the following choices were made:

- There are several potato handling-chains distinguishable (*e.g.* seed potato, starch potato, potato processing). The handling-chain of ware-potatoes, especially those for the fresh market was selected;
- Tubers of the cultivar Bintje, grade 50-60 mm, were used as biological test material;
- Although various types of damage exist, in this study emphasis was on impact induced subcutaneous tissue discolouration;
- The study comprised the chain from harvest up to packaging. Consequently the retailer and consumer phases of the chain are not taken into account.

Outline of the thesis

This thesis includes seven chapters. After this first chapter (General introduction), Chapter 2 describes from which links in the handling-chain subcutaneous tissue discolouration originates, and how much each link contributes. Also, the characteristics of representative Dutch ware-potato handling-chains in terms of construction (*e.g.* number and type of drops, drop heights) and utilization (*e.g.* transportation speed) were assessed.

Chapter 3 describes the number and intensity of impacts, recorded with an

instrumented sphere, in the different phases of representative Dutch ware-potato handling-chains. Specific questions as to which drop height onto a defined surface measured impacts correspond, and what the relation is between the number of impacts and damage are addressed.

Chapter 4 describes a new computer-controlled pendulum developed to simulate the range of impacts potatoes undergo in practice. Construction, configuration, operation and accuracy are discussed.

The relation between one or more doses of impact energy delivered at one tuber site and the resulting volume and depth of discoloured tissue is described in Chapter 5. The experiments focused on the effect of dose split, the effect of the number of impacts and on the effect of sequential impacts on subcutaneous tissue discolouration. The effect of susceptibility to subcutaneous tissue discolouration and the effect of storage duration were also studied.

In Chapter 6 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 is described. Also interactions between impact energy level and impact body shape in relation to the volume and depth of discoloured tissue are studied.

In the General discussion (Chapter 7) results from the study are integrated and discussed, and some recommendations with respect to future research are provided. Finally, the main conclusions of the work are summarized.

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CHAPTER 2

Subcutaneous tissue discolouration in ware-potatoes. 1. A chain analysis in the Netherlands

Abstract

In the long chain of handling operations potatoes are exposed to many short-time mechanical forces (impacts) and to long-term pressure. Impact and pressure can lead to subcutaneous tissue discolouration entailing qualitative and quantitative losses. We investigated the characteristics of construction and utilization of representative Dutch ware-potato handling-chains and from which links subcutaneous tissue discolouration originates. The number and height of drops appeared too high, the use of cushioning materials insufficient and the speed of the transporting parts too high and not in balance with each other. The contribution to the total amount of subcutaneous tissue discolouration was 16% for harvesting through bin-filling, 22% for storage, 27% for shovelling through truck loading and 35% for truck unloading through packaging. These contributions varied considerably within phases and within links. The results can be used to develop equipment, upgrade present chains and design new, produce-friendly handling-chains.

Keywords: blackspot, bruising, chain, damage, discolouration, handling, impact, potato, *Solanum tuberosum* L.

Introduction

Potato tubers pass through a long chain of handling operations in their way from the field to the consumer. Consequently they are exposed to many short-time mechanical forces (impacts) and to long-term pressure. Short-time impacts are caused by hits of tubers against parts of machinery and by tuber to tuber contacts. Piling causes long-term pressure during storage.

Impact and pressure can lead to different types of damage. An important one is subcutaneous tissue discolouration. Tissue discolouration, bruising, blackspot, tissue damage and other terms, though usually poorly defined, are often used to describe approximately the same phenomenon (for our definition see Materials and methods: *Susceptibility to subcutaneous tissue discolouration*). Subcutaneous tissue discolouration leads to qualitative and quantitative losses. Damage to potato tubers due to impact is one of the most important causes of loss of quality reported throughout the world. The considerable economic effects of subcutaneous tissue discolouration prompted

Chapter 2

comprehensive and intensive research efforts several decades ago. However, current information shows that although progress has been made, there is still a need for further research in order to offer consumers damage-free potatoes (Peters, 1996).

Subcutaneous tissue discolouration is caused at different points in the handling-chain: at the farm, at the grading/packaging (processing) centre and at the retailers. From which links in the handling-chain subcutaneous tissue discolouration originates and how much each link contributes was not known and was therefore investigated.

A data acquisition system referred to as an instrumented sphere (Zapp *et al.*, 1989) was developed to record the number and measure the intensity of impacts. The latter information was compared with data on subcutaneous tissue discolouration.

The present work addresses two questions:

- What are the characteristics of representative Dutch ware-potato handling-chains in terms of transportation distance, number and type of drops, drop heights, transportation speed, changes in speed and direction of transportation?
- From which links in the handling-chains does subcutaneous tissue discolouration originate and at what degree?

Molema *et al.* (1999) addresses the questions:

- What are the number and intensity of impacts, measured with an instrumented sphere, in different phases of representative Dutch ware-potato handling-chains?
- To which drop height on known surfaces do the measured impacts correspond?

Materials and methods

The potatoes

The research focused on ware-potatoes (*Solanum tuberosum* L. cv. Bintje, grade 50-60 mm), grown on sandy loam and clay soils ($38 \pm 9\% < 16 \mu\text{m}$) in the Netherlands under the usual regime. For ware-potatoes this regime comprised: planting in April, harvest in September/October and chemical haulm killing some weeks prior to harvest (Van Loon *et al.*, 1993). Potatoes were from one growing season. At the time of this study cv. Bintje was the most popular cultivar and shows an average susceptibility to subcutaneous tissue discolouration (Parlevliet *et al.*, 1992).

Selection of grading/packaging centres and growers

The research started with a survey of grading and packaging centres. Three grading/packaging centres for ware-potatoes, representing the Dutch style of ware-potato handling, were selected for the survey and 21 growers (purveyors) participated

(seven per grading/packaging centre). Each grading/packaging centre is assumed to be representative for a certain style of handling.

These styles are:

- produce-friendly;
- less produce-friendly;
- least produce-friendly.

The style of handling for each centre was categorized by experts.

Four phases

The handling-chain was divided into four phases; each phase consisted of one or more links. A schematic representation of the common Dutch ware-potato handling-chain is given in Figure 2.1. The Phase Harvest comprises the links lifting (a), transportation from the field and self-unloading of the hopper (b) and bin-filling (c) at the farm. The Phase Storage comprises the link storage (d). The Phase Transport comprises the links shovelling (e) and truck loading (f) at the farm. The Phase Packaging comprises the links truck unloading (g), first interim storage (h), grading (i), second interim storage (j), washing (k), third interim storage (l) and packaging (m) of the tubers in consumer units (2.5 or 5.0 kg) at the grading/packaging centre. Each centre used at least two of the three possible interim storages. In this study transport to and handling in the shop were not included. In the Phase Harvest, nine growers (three per centre) participated and another comparable group of twelve growers (four per centre) participated in the other phases. Since the effect of storage duration was not aim of this study, two groups of growers participated because time of delivery of the potatoes to the grading/packaging centres depends from a number of factors and differs largely. So, for the Phases Storage through Packaging a new group of growers was selected with a small range in time of delivery.

Analysis of the handling (processing) chain

Per grower and grading/packaging centre the transportation distance, number and type of drops (e.g. cushioned or non-cushioned), drop heights, transportation speed and changes in speed and direction of transportation were determined.

Sampling, assessment of samples and index calculation

The following variables were determined at the level of growers.

Dirt tare. Both after lifting the potatoes and after self-unloading of the hopper two samples of 25 kg each were taken to estimate the amount of dirt tare. Five subsamples were pooled into one sample. The amount of dirt tare was calculated on the basis of

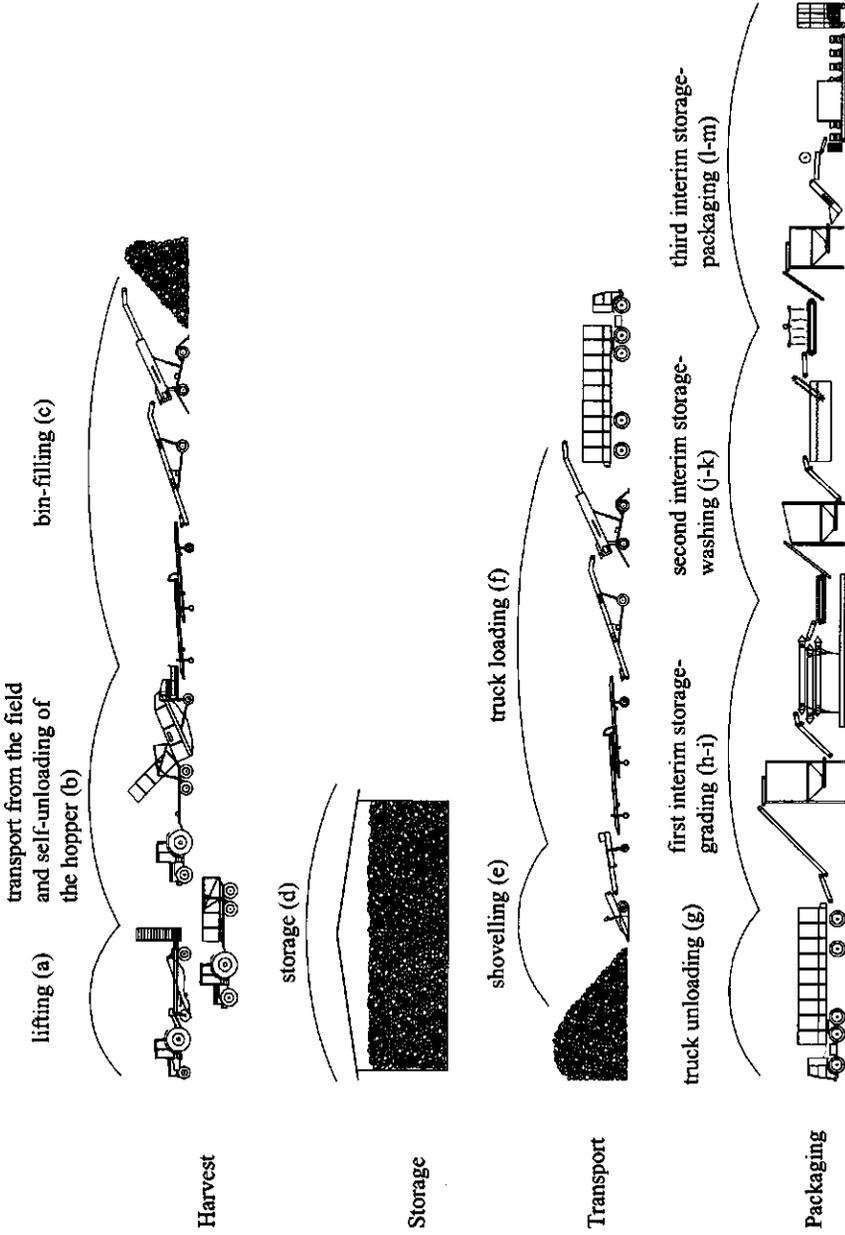


Figure 2.1. Schematic representation of the common Dutch ware-potato handling-chain, divided in phases (Harvest through Packaging) and in links (a through m).

gross weight.

Soil moisture. To estimate the soil moisture, samples of 0.5 kg (five subsamples were pooled into one sample) were taken from the ridge in the middle of the distance between consecutive plants. The soil moisture was calculated on the basis of oven-dry weight (24 h at 104 °C).

Dry matter content. In the Phase Harvest two samples and in the Phases Storage through Packaging four samples of 5 kg were taken to assess the dry matter content. The dry matter content was calculated from under-water weight as reported by Van Es & Hartmans (1987).

Temperature. Tuber temperature and ambient temperature were measured ten times before lifting (Phase Harvest) and before shovelling (Phase Transport). Tuber temperature was measured 1 cm below the skin.

Storage duration. Storage duration (Phase Storage) of the batches was registered.

Susceptibility to subcutaneous tissue discolouration. In this chapter subcutaneous tissue discolouration encompasses all blue and blue-grey deviation in tissue colour relative to the surrounding tissue. In the Phase Harvest two samples and in the Phases Storage through Packaging four samples of 100 tubers were taken to determine the susceptibility to subcutaneous tissue discolouration. Therefore the samples (100 tubers each) were shaken on a shaking table according to Dutch standards (shaking area 1 m²; up- and downward displacement 30 mm; shaking frequency 290 rpm; shaking time 30 s). After 72 h at 15 °C the tubers were peeled by a peeling machine (Eillert B-12p) and assessed for the percentage of the tuber surface containing tissue discolouration, according to the following Dutch standard (Meijers & Kleijburg, 1973; Van Loon & Meijers, 1975; Van Loon & Meijers, 1980; Buitelaar, 1993): none (0%), light (0-2%), moderate (2-10%) and heavy (> 10%). The characterization of susceptibility to subcutaneous tissue discolouration of batches is given in Table 2.1.

Susceptibility of batches to subcutaneous tissue discolouration is expressed as index number calculated as follows:

$$\text{subcutaneous tissue discolouration} = \frac{1x n_{\text{light}} + 2x n_{\text{moderate}} + 3x n_{\text{heavy}}}{6}$$

and ranges from 0 through 50. In the formula n_{light} , n_{moderate} and n_{heavy} represent the number of tubers with light, moderate and heavy subcutaneous tissue discolouration, respectively.

Subcutaneous tissue discolouration. At the end of each link (a through m) samples were taken to determine the amount of subcutaneous tissue discolouration caused by impact or long-term pressure (piling). Four samples of 60 kg (in the Phase Harvest two samples of 60 kg) were taken out of an amount of ca 60 tons. Each sample of 60 kg consisted of four subsamples of 15 kg each. From each subsample 25 tubers were chosen at random. Finally this procedure resulted in four (in the Phase Harvest two) samples of 100 tubers (per grower per link). After 72 h at 15 °C the tubers were peeled

Chapter 2

Table 2.1. Characterization of susceptibility of batches to subcutaneous tissue discolouration according to the calculated index.

Index	Characterization of susceptibility
0.0 - 3.9	None to light
4.0 - 9.9	Light to moderate
10.0 - 17.9	Moderate to heavy
≥ 18.0	Heavy

by a peeling machine for assessment. Samples were assayed for fresh subcutaneous tissue discolouration, similar to those for determination of susceptibility to subcutaneous tissue discolouration. In the Phases Storage through Packaging subcutaneous tissue discolouration, resulting from the Phase Harvest, was determined in the same way by assessment of 'old discolouration', visible as more or less corked tissue. Potato batches of the two comparable groups of growers were comparable with respect to different aspects studied. With respect to subcutaneous tissue discolouration, caused in the Phase Harvest, this assumption is confirmed (see Results and discussion). Therefore calculation of the extend of subcutaneous tissue discolouration per phase was finally based on the results from the group of growers participating in the Phases Storage through Packaging. To differentiate subcutaneous tissue discolouration within the Phase Harvest (links a, b and c) the results from the growers participating in the Phase Harvest were used.

Data processing

All measurements were done at the level of growers or grading/packaging centres. Finally the measurements were averaged and standard deviations were calculated. Standard deviations are affected by the selection of centres and their purveyors. Variation in subcutaneous tissue discolouration, expressed as index, was ascribed to various sources.

Results and discussion

Starting material and experimental conditions

Details on the starting material and the experimental conditions are given in Table 2.2. The potatoes were harvested under wet conditions resulting in a high percentage of dirt tare. The cleaning effect of the self-unloading hopper, calculated on the basis of dirt tare (% of gross weight) after the harvester, was 43% on average (data not shown). Tuber and ambient temperature during harvest and handling were relatively low. On

average, the potato batches showed a moderate to heavy susceptibility to subcutaneous tissue discolouration (Table 2.2). Potato batches were from two different groups of growers to avoid effects of a large variation in storage duration (as a consequence of time of delivery) which was not the purpose of this study.

Analysis of the handling (processing) chain

The construction of the chain (Figure 2.1) entailed drops, changes in direction, *etc.* of which the numbers and the category they belong to were determined by analyzing the chain.

Transportation distance. On average, the potatoes travelled 346 m on their way through the handling-chain. The distance comprised 43 (range 38-49) and 39 (range 19-47) m of transportation into and out of the shed, respectively, plus another 264 (range 217-335) m for grading, washing and packaging. In the Phase Harvest the differences between growers were small. The distance the potatoes travelled on their way through the handling-chain may have influence on the extent of subcutaneous tissue discolouration, dependent on *e.g.* the accompanying number of impacts *etc.*

Drops and drop type. The entire handling-chain comprised on average 72 drops with heights exceeding 10 cm, 49 (68%) of which even exceeded 30 cm (Table 2.3). During

Table 2.2. Experimental conditions and characteristics of material (standard deviation), given for four phases in the chain.

Phase	Experimental conditions and characteristics of material						
	Soil moisture (%)	Dirt tare (%)	Tuber dry matter content (%)	Temperature (°C)		Storage duration (d)	Susceptibility to subcutaneous tissue discolouration (index)
				Tuber	Ambient		
Harvest ^a	24(3) ^c	26(11) ^d 15 (4) ^e	19(1)	12(4) ^c	13(3) ^c		11(8)
Storage ^a			21(1)			176(19)	11(3)
Transport ^a		5 (4) ^f	21(1)	13(3)	7(2)		11(3)
Packaging ^b			21(1)				11(3)

^a standard deviation given for growers.

^b standard deviation given for centres.

^c at harvest.

^d after lifting.

^e after self-unloading hopper.

^f during truck loading.

lifting and on the conveyor belts, *etc.* used to transport the tubers into the shed on average 11 drops with heights exceeding 10 cm, six of which exceeded 30 cm, occurred. In the case of the equipment used to remove the tubers from the shed these numbers were 7 and 6, respectively. During grading, washing and packaging on average 54 drops, 37 of which exceeded 30 cm, occurred.

Cushioning and/or fall breakers were involved in *ca* 50% of the drops (Table 2.4). On average, in 27 cases within the chain the tubers were dropped from a conveyor belt onto guide (supporting) rolls or another hard surface.

In the chains the number and the height of drops were too high and the use of cushioning materials insufficient to achieve an acceptable level of subcutaneous tissue discolouration according to the generally adopted Dutch CKA (Commissie Kwaliteitskeuring Aardappelen; Committee for Quality Inspection of Potatoes) norms (Buitelaar, 1993). Van Loon & Meijers (1980) and De Haan (1987) suggested, to keep damage at an acceptable rate, that drop height should not exceed 30-40 cm. However, Molema *et al.* (1997a) found that the occurrence of subcutaneous tissue discolouration could also occur as the result of repetitive low-energetic impacts at the same tuber site.

When drop height exceeds the tolerated level, efficient and properly-designed facilities should be used *e.g.* by incorporating cushioning, fall breakers and downward travelling conveyor belts. Bulk conveyors can be equipped with height control sensors to minimize drop height. Good cushioning decelerates the tuber more efficiently than a hard surface, and it spreads the impact force over a larger area. Misener *et al.* (1992) reported a significant positive correlation between the damage index and the number of drops and cumulated drop height on the packaging lines. Equipment has to be kept filled with tubers to capacity as much as possible.

Changes in direction of transportation. In considering the number of changes in direction bouncing of tubers was disregarded. The entire handling-chain included on average 29 changes in direction of 61-90° (Table 2.5). Changes in direction in the class

Table 2.3. Number of drops (standard deviation), grouped by drop height, given for four phases in the chain.

Phase	Drop height class (cm)						Total
	11-20	21-30	31-40	41-50	51-60	> 60	
Harvest ^a	1 (0.8)	4 (1.0)	3 (1.0)	1 (1.0)	1 (0.6)	1 (0.7)	11 (0.8)
Storage ^a	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
Transport ^a	0 (0.0)	1 (0.8)	1 (1.2)	2 (0.7)	2 (0.9)	1 (0.9)	7 (2.2)
Packaging ^b	4 (3.8)	13 (4.2)	19 (2.9)	7 (3.5)	4 (3.5)	7 (3.5)	54 (2.5)
Total	5	18	23	10	7	9	72

^a standard deviation given for growers.

^b standard deviation given for centres.

Table 2.4. Number of drops on non-cushioned and cushioned surfaces (standard deviation) given for four phases in the chain.

Phase	Non-cushioned	Cushioned		
		Rubber conveyor	Rubber fall-breaker	Rubber conveyor and rubber fall-breaker
Harvest ^a	5 (1.4)	6 (1.0)	0 (0.0)	0 (0.0)
Storage ^a	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
Transport ^a	3 (1.6)	4 (1.5)	0 (0.0)	0 (0.0)
Packaging ^b	27 (11.5)	19 (2.9)	0 (0.0)	8 (13.9)
Total	35	29	0	8

^a standard deviation given for growers.

^b standard deviation given for centres.

Table 2.5. Number of changes in direction (standard deviation), grouped into classes, incurred in the four phases in the chain.

Phase	Class of changes in direction (°)			
	31-60	61-90	Variable	Total
Harvest ^a	1 (0.8)	2 (0.5)	1 (0.0)	4 (0.8)
Storage ^a	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
Transport ^a	0 (0.0)	1 (0.7)	2 (0.9)	3 (1.4)
Packaging ^b	1 (1.7)	26 (7.8)	0 (0.0)	27 (7.2)
Total	2	29	3	34

^a standard deviation given for growers.

^b standard deviation given for centres.

1-30° were not found. A 'variable' change in direction means that the direction of transportation changed during work, e.g. in the case of a swerving bin-filler. On average, ca 50% of the registered drops (Table 2.3) involved a change in direction resulting in extra impact between tubers and the material they fell on.

Transportation speed and changes in transportation speed. The speed of conveying belts and other transporting parts was often high (Table 2.6, upper part) and not in balance with each other (Table 2.6, lower part). Of the measured transport speeds, 46% exceeded 0.6 m s⁻¹ and 8% exceeded 0.9 m s⁻¹. Although 63% of the differences in speed was less than 0.51 m s⁻¹, still 13% of the differences in speed exceeded 0.5 m s⁻¹. Speed differences exceeding 1.5 m s⁻¹ were not observed. In presenting speed

differences only absolute values are presented. In some cases speed and thus speed differences were practically not detectable. Van Loon & Meijers (1980) and De Haan (1987) suggested that conveyor speed must not exceed 0.5 m s^{-1} . High transport capacity must therefore not be obtained by a faster belt speed but by heavier loading per unit length. The consequence is either a wider belt or a thicker layer of potatoes on the belt. De Haan (1987) stated that the energy to be absorbed at the end of a fall among other things depends on conveyor speed.

Quantification of impact. The effect of energy transfer in the handling-chain (Figure 2.1) was quantified directly by measurements with an instrumented sphere containing a tri-axial accelerometer. These results were reported in Molema *et al.* (1999).

Subcutaneous tissue discolouration

The total amount of subcutaneous tissue discolouration incurred over the entire chain, expressed as index, was set at 100%. To calculate the index for subcutaneous tissue

Table 2.6. Speed of transport (upper part of the table) and number of differences in speed (lower part of the table), grouped into classes, given for four phases in the chain (standard deviation).

Phase	Speed class (m s^{-1})				Not detectable	Total
	0.00-0.30	0.31-0.60	0.61-0.90	> 0.90		
Harvest ^a	3 (0.3)	4 (2.5)	9 (2.1)	3 (2.0)	1 (2.1)	19 (2.3)
Storage ^a	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
Transport ^a	2 (0.0)	0 (0.0)	6 (3.3)	3 (1.9)	0 (0.0)	10 (4.5)
Packaging ^b	10 (3.0)	15 (1.5)	17 (3.0)	1 (0.6)	11 (1.0)	54 (7.5)
Total	15	19	32	7	12	83

	Speed difference class (m s^{-1})				Not detectable	Total
	0.00-0.50	0.51-1.00	1.01-1.50			
Harvest ^a	14 (2.1)	3 (1.2)	0 (0.0)	2 (2.5)		19 (1.9)
Storage ^a	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)		0 (0.0)
Transport ^a	7 (4.9)	2 (0.9)	1 (0.7)	0 (0.0)		10 (5.2)
Packaging ^b	31 (5.8)	5 (1.2)	0 (0.0)	17 (2.9)		53 (7.5)
Total	52	10	1	19		82

^a standard deviation given for growers.

^b standard deviation given for centres.

discolouration for the Phase Harvest of the growers participating in the Phases Storage through Packaging, the average indices of old subcutaneous tissue discolouration (see Materials and methods) were taken. These indices (3.1 ± 2.2) corresponded with the indices for subcutaneous tissue discolouration caused in the Phase Harvest of the other group of growers (3.3 ± 2.2). So, the increase attributable to the different phases could be calculated from the same batches of potatoes originating from the group of growers participating in the Phases Harvest through Packaging. The contribution of each phase to total discolouration is given in the right-most column of Table 2.7. The average index for subcutaneous tissue discolouration at the end of the Phases Harvest through Packaging was 19.4 and ranged from 13.9 to 26.1. The relative contribution to the total amount of subcutaneous tissue discolouration was highest in the Phase Packaging and lowest in the Phase Harvest. This contribution varied per centre and may differ in other years.

Figure 2.2 shows the absolute indices for subcutaneous tissue discolouration for links a through m. To differentiate subcutaneous tissue discolouration within the phases, for the Phase Harvest the results from the growers participating in that phase were used. It was impossible to obtain this information from the batches used in the Phases Storage through Packaging.

In the Phase Harvest, lifting caused *ca* 90% of the subcutaneous tissue discolouration within this phase. Probably due to the bad soil conditions (still 26% dirt tare after the harvester) during lifting the vertical agitation needed for a sufficient soil sieving process on the web caused extra impacts between the web rods and the potatoes. The self-unloading hopper hardly contributed to the build-up of subcutaneous tissue discolouration, probably also due to the relative large amount of dirt tare. Most of the subcutaneous tissue discolouration was caused during and after storage (from link d onwards *ca* 85%). Storage (link d) had the largest effect on subcutaneous tissue discolouration (22%). Most of this tissue discolouration may be a consequence of pressure spots due to imperfect ventilation which leads to moisture loss (Hughes, 1980). Differences between growers in the effect of storage (pressure spots) were great

Table 2.7. Increase of subcutaneous tissue discolouration (index) for the Phases Harvest through Packaging given for three grading/packaging centres (A, B, C) averaged over four growers per centre.

Phase	Index			Mean (% of total)
	A	B	C	
Harvest	1.9	2.3	5.0	3.1 (16)
Storage	2.4	3.3	7.2	4.3 (22)
Transport	4.3	5.0	6.4	5.2 (27)
Packaging	5.3	7.7	7.5	6.8 (35)
Total	13.9	18.3	26.1	19.4 (100)

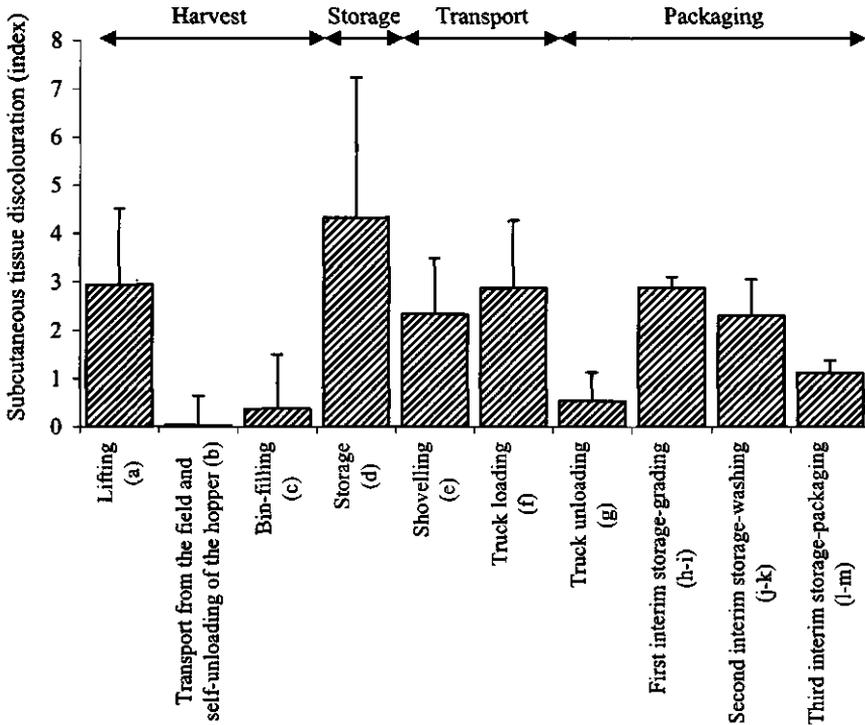


Figure 2.2. Increase of subcutaneous tissue discolouration per link(s) expressed as index. For links a, b and c averages over growers ($n = 9$), links d, e and f averages over growers ($n = 12$) and for links g, h-i, j-k and l-m averages over centres ($n = 3$) are given (vertical bar indicates standard deviation).

(range 8-40%). In the Phase Transport both shovelling and truck loading contributed considerably to the total amount of subcutaneous tissue discolouration. Within the Phase Packaging grading caused most subcutaneous tissue discolouration. In this link the variation was small just as at packaging. Approximately 35% of the subcutaneous tissue discolouration caused in the Phase Packaging was attributable to interim storage in bunkers. In this context, interim storage includes the extra transportation route used for interim storage. No significant difference in subcutaneous tissue discolouration index was observed between 2.5 and 5.0 kg consumer units (data not shown).

McRae (1986) also found that mechanical damage is cumulative throughout the stages of harvesting and handling. Due to the cumulative effect the absolute increase of subcutaneous tissue discolouration may be underestimated towards the end of the chain, especially when batches are susceptible to discolouration. In this case improvements in the beginning of the handling-chain will probably result in a relatively larger amount of subcutaneous tissue discolouration caused in the other links of the handling-chain.

As a consequence of the experimental set up, based on the research questions stated, no concrete relationship could be established between the specific data found in the analysis of the chain such as length, drop height, *etc.* and the indices for subcutaneous tissue discolouration. Possible effects are included in the effect of produce-friendliness and can not be differentiated (see *Explanation of variation*).

In this analysis samples were assessed for subcutaneous tissue discolouration on the surface after peeling (inherent to the Dutch standards we used). However, it became clear from more recent experiments (Molema *et al.*, 1997a, b) that the depth of discoloured tissue also has to be considered.

Explanation of variation

In the Phase Harvest the susceptibility to subcutaneous tissue discolouration and the tuber temperature together accounted for 96% of the variation in subcutaneous tissue discolouration, calculated as indicated by Payne *et al.* (1993). The greater contribution was by the susceptibility to tissue discolouration. In the Phases Storage through Packaging, 80% of the variation was attributable to the temperature of the tuber and the ambient temperature at removal from the shed and to differences in the produce-friendliness of the different grading/packaging centres. The tuber temperature, which was often too low, was the most influential of these factors.

Many authors (*e.g.* Ophius *et al.*, 1958) showed a negative relationship between handling temperature and blackspot discolouration. Johnson & Wilson (1969) showed that the variation in bruise resistance was accounted for *ca* 46% by variation in temperature. Peterson & Hall (1974) found the same tendency.

We ascribed the large amount of pressure spots after storage to the large pile height and to improper ventilation and drying. Due to the wet conditions (dirt tare) at harvest the amount of subcutaneous tissue discolouration including pressure spots could be overestimated because a higher drying rate than normally was required. As the tuber increasingly loses moisture, the tissue tension declines and susceptibility to discolouration increases (Kunkel & Gardner, 1965).

Practical implications

Heating. Much subcutaneous tissue discolouration can be prevented by adequate temperature control of the tubers, especially when the ambient temperature is low at the time of delivery. Meijers & Rastovski (1987) recommended that the batches, depending on their susceptibility to blackspot, should be warmed before handling after storage to a minimum of 12 to 18 °C. However, batches which are extremely susceptible need a higher temperature.

Interim storage. The use of bunkers can be reduced by a more efficient planning.

Upgrading present chains. The speed of conveyor belts and other transporting units can in many cases be reduced and better geared. The advantages of reductions in speed are

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a buffering effect and consequently lower drop heights. However, in this research the disadvantage of e.g. extra friction tubers are exposed to could not be proven from the results, the large number of changes in direction can be drastically reduced. Pressure spots after storage could be greatly reduced by using a better storage technique, i.e. using not more ventilation than absolutely necessary for drying and cooling the potatoes.

Developing new chains. Making improvements in the present chains can reduce the amount of subcutaneous tissue discolouration. But it is not certain whether those improvements will eventually result in an acceptable level of subcutaneous tissue discolouration according to the commonly used Dutch CKA norms (Buitelaar, 1993). To ensure an end-produce with a low level of subcutaneous tissue discolouration in most years, the handling-chains will have to be adjusted drastically. The number of drops and drop heights and the number of changes in speed and direction will all have to be reduced. The use of pallet boxes seems to be a good alternative. In that way the number of operations and pile height can be minimized and consequently the occurrence of subcutaneous tissue discolouration and pressure spots will be limited.

To obtain a significant reduction in the level of subcutaneous tissue discolouration, optimal utilization of technique and technology is important.

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CHAPTER 3

Subcutaneous tissue discolouration in ware-potatoes. 2. Impact measured by an instrumented sphere

Abstract

Potatoes are exposed to mechanical forces, which can lead to subcutaneous tissue discolouration resulting in losses. We investigated the number and intensity of impacts in different phases of representative Dutch ware-potato handling-chains using an instrumented sphere (IS). Further questions were to which drop height onto a defined surface do measured impacts correspond, and what is the relation between the number of impacts and damage? Close relationships between peak-acceleration and velocity-change for different drop heights were found for various cushioning materials, allowing interpretation of impact measurements in terms of drops. The IS recorded *ca* 340 impacts exceeding 30 g. The contribution to the total number of impacts was 11% for Harvest, 0% for Storage, 10% for Transport and 79% for Packaging. The number and intensity of impacts correlated well with the amount of subcutaneous tissue discolouration. It is concluded that the produce-friendliness of the handling-chains can be improved.

Keywords: blackspot, bruising, damage, discolouration, handling, impact, instrumented sphere, potato, *Solanum tuberosum* L., velocity-change

Introduction

Potato tubers are exposed to mechanical forces by impact and pressure. Impact and pressure can lead to subcutaneous tissue discolouration (bruising, damage) entailing qualitative and quantitative losses. We defined (Molema *et al.* 1999) subcutaneous tissue discolouration as all blue and blue-grey deviations in tissue colour relative to the surrounding tissue. We reported there from which links in the handling-chain subcutaneous tissue discolouration originates and how much each link contributes. Characteristics of representative Dutch ware-potato handling-chains in terms of construction (*e.g.* number and type of drops, drop heights) and utilization (*e.g.* transportation speed) were also reported there.

In an effort to characterize the mechanical forces leading to bruising, an instrumented sphere IS100 (IS) was developed (Zapp *et al.*, 1989a, b; Morrow & Ruscitti, 1990). The IS is a micro-controller-based data acquisition unit for quantifying impacts that occur during produce handling. The IS is an excellent tool to establish the

number of impacts above a certain threshold and to identify links that may cause damage in mechanical handling-chains of various agricultural produce (Sarig *et al.*, 1992). Also Morrow & Ruscitti (1989, 1990) demonstrated that the IS is a useful device to indicate links of potential damage in handling equipment and that the IS can assess relative levels of impact exposure at different links in the handling-chain. Fluck & Ahmed (1973) showed that bruising results from a complex relationship between acceleration force, velocity-change and impact duration, all of which have to be considered.

The IS was collaboratively developed by the Agricultural Research Service (ARS) of the United States Department of Agriculture (USDA), Michigan Agricultural Experimental Station and Michigan State University, originally, to analyze apple handling systems. The most relevant information that can be extracted from the IS is an accurate description of impacts in terms of peak-acceleration and velocity-change (Armstrong *et al.*, 1991; Sober *et al.*, 1989). Peak-acceleration G expressed in g (acceleration due to earth's gravity: 9.81 m s^{-2}) is defined as the maximum acceleration value for each impact; velocity-change is the acceleration integrated over time (Zapp *et al.*, 1989a) as illustrated in the Materials and methods section of this chapter. For impacts on a hard surface the impact curve is characterized by a high peak-acceleration and a short impact duration. For impacts on padded surfaces, the peak-acceleration is lower but the duration is longer and therefore the resulting velocity-change is larger. Because of extreme variation in susceptibility to subcutaneous tissue discolouration among potatoes, the device should not be used to predict whether the produce will be damaged but rather to give an output that can be quantified as the equivalent height of a drop onto a defined surface.

In representative Dutch ware-potato handling-chains the number and intensity of impacts, their quantification in terms of drops on defined surfaces and the relation between these variables and subcutaneous tissue discolouration were not known.

Therefore the present work addresses three questions:

- How frequent and intense are impacts in different phases of representative Dutch ware-potato handling-chains?
- To which drop height onto a defined surface do the measured impacts correspond?
- What is the relation between the number of impacts and subsequent subcutaneous tissue discolouration?

Materials and methods

Instrumented sphere

The IS has a diameter of 86 mm, weights 304 g and can measure impacts up to 500 g

with an accuracy of *ca* 3%. These properties render the IS suitable to evaluate potato handling systems (Hyde *et al.*, 1992).

The IS (Figure 3.1) consists of a tri-axial accelerometer, a central processing unit, data storage and a rechargeable power supply. The tri-axial configuration is essential for monitoring the resultant magnitude of impacts imposed upon the IS (Tennes *et al.*, 1988). For more technical details see Zapp *et al.* (1989b) and Tennes *et al.* (1988).

The impact sampling rate and the acceleration threshold can be set prior to use via a computer (Figure 3.1). When the IS is in operation it is disconnected from the interface and measurements can be taken. After data collection, data can be transferred to the computer via an interface for analysis and storage.

Impact reference measurements with a drop simulator

To study the correspondence of measured impacts with drops on defined surfaces a vertical telescope device with a vacuum attachment and an electronic air valve was used as a drop simulator (Figure 3.2). The IS was arrested by vacuum. The IS was then released and dropped without rotating on a (covered) steel plate. The procedure was repeated ten times, with the IS positioned randomly at the vacuum attachment. The drop simulator, which allowed the IS to free-fall onto the impact surface from a series of heights, was used to evaluate four materials commonly used in Dutch potato handling-chains. The materials were: 30 mm steel, 30 mm steel covered with 3.4 mm PVC, 30 mm steel covered with 6 mm rubber and 30 mm steel covered with 11 mm rubber foam (cell-rubber). For details about the materials used see Table 3.1. Drop heights ranged from 1 to 80 cm.

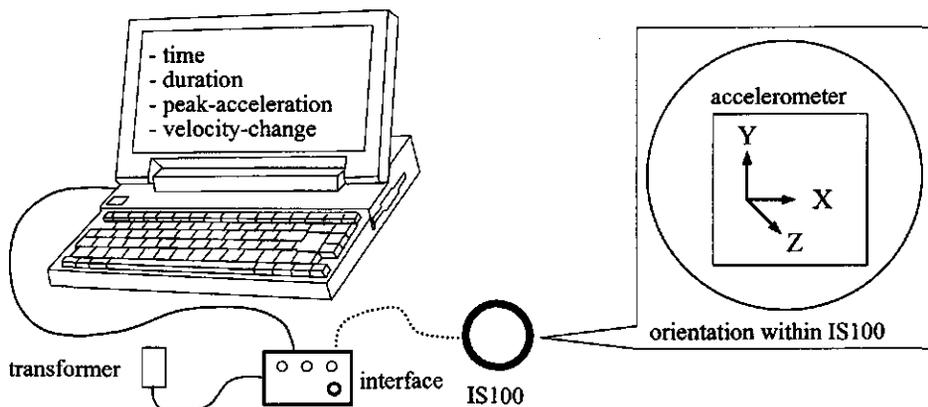


Figure 3.1. Schematic representation of the IS-configuration (after Anonymous, 1990).

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Table 3.1. Characteristics of the materials used for the reference impact measurements.

Characteristic	Material			
	Steel	PVC	Rubber	Rubber foam
Components	Carbon steel	Flexam 80 Flexam 95 2 inlayers	Styreen Butadieen Rubber A9506 1 inlayer	Cell rubber Polyurethane toplayer
Thickness (mm)	30	3.4	6	Cell rubber 10 Polyurethane toplayer 1
Hardness *				
- degrees Shore A			70 (+/- 7)	15
- Brinell	130			
Colour	Natural	Green	Black	Cell rubber – black Polyurethane toplayer – brown
ISO registration	St. 37-2	-	SBR	-

* Hardness expressed according to different methods.

Impact measurements

Impacts were recorded by the IS (sampling rate 3,906 Hz) as it moved with potatoes during normal operation. The IS was placed ten times (Brook & Guyer, 1990; Bollen & Cox, 1991; Brook, 1991) at the initial point of pre-defined links to record the impacts above a threshold value of 30 g (Brook & Guyer, 1990). Figure 3.3 gives a schematic representation of an impact curve. Velocity-changes were calculated with the acceleration values.

The potatoes and selection of grading/packaging centres and growers

Measurements were carried out in potato handling-chains during normal operation (flow) in ware-potatoes (*Solanum tuberosum* L. cv. Bintje). In Molema *et al.* (1999) we reported on sampling, analysis of samples and calculation of the index for subcutaneous tissue discolouration.

Three grading/packaging centres and 21 purveyors to the centres, which reflect the major Dutch styles of potato handling, were selected for the research (Molema *et al.*, 1999).

Phases in the handling-chain

The handling-chain was divided into phases and links. For a schematic representation of the common Dutch ware-potato handling-chain see Molema *et al.* (1999). The Phase

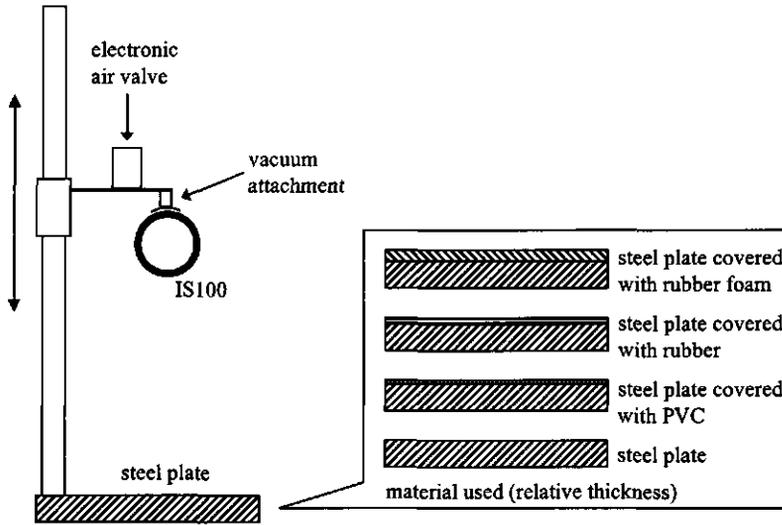


Figure 3.2. Schematic representation of the drop simulator and (combinations of) materials used in experiments. For materials used see also Table 3.1.

Harvest comprised lifting, transportation from the field, self unloading of the hopper and bin-filling at the farm. The Phase Storage comprised storage. The Phase Transport comprised shovelling and truck loading at the farm. The Phase Packaging comprised truck unloading, first interim storage, grading, second interim storage, washing, third interim storage and packaging of the tubers into consumer units at the grading/packaging centre. Each grading/packaging centre used at least two of the three possible interim storages. In the Phase Harvest, nine growers participated and another comparable group of twelve growers participated in the other phases.

Data processing

Impact reference measurements. For each material tested peak-acceleration and velocity-change were analyzed as a function of drop height.

Impact measurements. Impact pulses recorded by the IS as it moved with potatoes through the handling-chain were analyzed to determine peak-acceleration and velocity-change. For each phase (one or more link(s)), impacts were classified according to peak-acceleration and velocity-change. We preferred this procedure above alternatives described in literature such as the ones by Brook & Guyer (1990), because our procedure allows optimal use of the data.

Correlation between impact measurements and subcutaneous tissue discolouration. For each phase the number of impacts and subsequent subcutaneous tissue discolouration were compared to establish the relation between these parameters. Subcutaneous tissue discolouration was recorded after each phase and data were

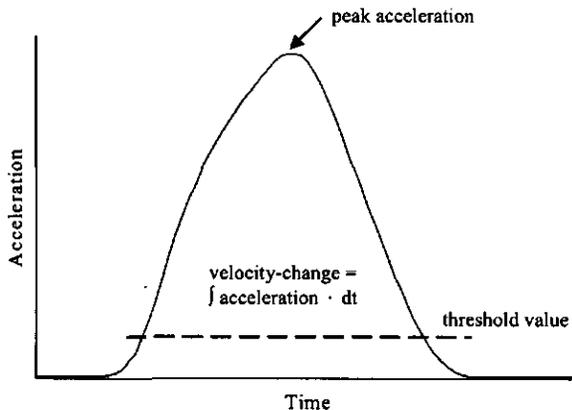


Figure 3.3. Schematic representation of an impact, and calculation of the velocity-change.

reported earlier (Molema *et al.*, 1999). In this chapter these data are related to the number of impacts per phase as assessed with the IS100.

Results

Impact reference measurements

For the materials tested a straightforward relationship between peak-acceleration and velocity-change was found (Figure 3.4). Peak-acceleration and velocity-change increased with an increase in drop height. Impacts on a hard surface (*e.g.* steel) led to high peak-accelerations and low velocity-changes. Impacts on a well-padded surface (*e.g.* rubber foam on steel) led to low peak-acceleration and high velocity-changes. There was no difference between the effects of steel and of steel covered with PVC. The energy absorbing capacity of rubber foam was much higher than that of the other materials. A 6 mm rubber cover on steel increased the energy absorbance considerably, relative to uncovered steel.

Impact measurements

The impacts recorded are grouped into classes of peak-acceleration and velocity-change and cumulated for the whole chain from lifting through packaging (Figure 3.5). In the entire chain the IS recorded on average 340 impacts exceeding 30 g. The number of impacts was 38 into (Phase Harvest) and 35 out of (Phase Transport) the shed (Table 3.2 and 3.3, respectively), plus another 266 in the Phase Packaging for grading, washing and packaging (Table 3.4).

In the entire chain on average 98% of the impacts did not exceed 150 g, 58% of the impacts was in the class 30-50 g and 45% was in the velocity-change class 0.6-1.0 m s⁻¹. In the Phases Harvest and Transport the maximum peak-acceleration of the recorded impacts was in the class 351-400 g, and in the Phase Packaging impacts with a peak-acceleration > 400 g were recorded incidentally. Maximum velocity-change of the assessed impacts in the Phases Harvest, Transport and Packaging was in the classes 5.1-5.5, 5.6-6.0 and > 6.1 m s⁻¹, respectively. Differences in relative frequency of impacts per class of peak-acceleration and of velocity-change for the Phases Harvest through Packaging were small (maximum deviation of absolute percentage values 7%). When the frequency in certain classes was low, variation was large.

Drop height and material (type of drop) corresponding to a certain combination of peak-acceleration and velocity-change can be characterized by the data of Figure 3.4.

Impact measurements and subcutaneous tissue discolouration

The average index for subcutaneous tissue discolouration at the end of the four phases was 19.4 (Molema *et al.*, 1999). The contribution to this index for the individual Phases Harvest, Storage, Transport and Packaging was 3.1, 4.3, 5.2 and 6.8, respectively. Despite the absence of impacts, storage (Phase Storage) had a considerable effect on subcutaneous tissue discolouration. This effect is a consequence of static load resulting in pressure spots. The average number of impacts in the Phases Harvest, Storage, Transport and Packaging was 38, 0, 35 and 266, respectively. The average number of impacts above 100 g was 3, 0, 3 and 20 respectively.

In Figure 3.6 the proportions of the number of impacts below 100 g, the proportions

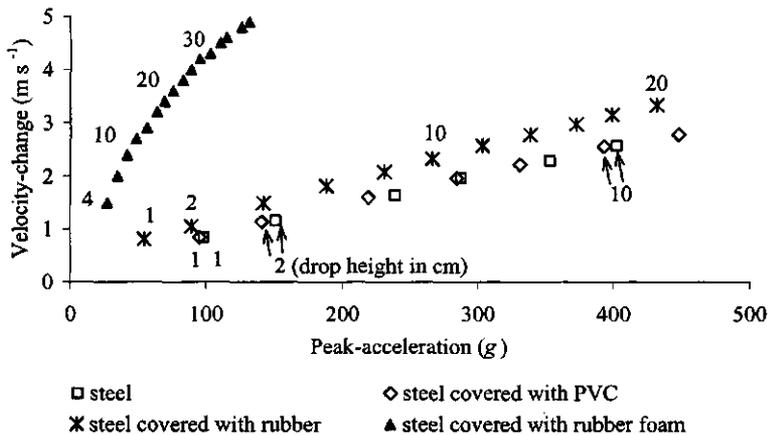


Figure 3.4. Velocity-change versus peak-acceleration for drops from different heights on four materials. Drop heights (in cm) are plotted with the corresponding data points. For materials used see Table 3.1.

Table 3.2. Number of impacts, grouped into classes of peak-acceleration and velocity-change, given for the Phase Harvest in the handling-chain: lifting, transportation from the field, self unloading of the hopper and bin-filling at the farm (standard deviation of the average for the participating growers).

Peak-acceleration class (g)	Velocity-change class (m s ⁻¹)								Total	
	0.0-0.5	0.6-1.0	1.1-1.5	1.6-2.0	2.1-2.5	2.6-3.0	3.1-3.5	3.6-4.0		> 4.0
30- 50	3.33 (1.25)	11.03 (1.65)	3.10 (0.98)	0.96 (0.66)	0.39 (0.28)	0.10 (0.17)	0.11 (0.17)	0.07 (0.10)	0.00 (0.00)	19.09 (2.93)
51-100	0.19 (0.14)	5.78 (2.06)	5.88 (1.92)	2.50 (0.49)	0.69 (0.18)	0.31 (0.19)	0.11 (0.14)	0.07 (0.11)	0.03 (0.07)	15.56 (2.77)
101-150	0.00 (0.00)	0.23 (0.16)	0.62 (0.35)	0.91 (0.40)	0.46 (0.22)	0.18 (0.20)	0.11 (0.12)	0.04 (0.05)	0.02 (0.04)	2.58 (0.82)
151-200	0.00 (0.00)	0.00 (0.00)	0.13 (0.22)	0.14 (0.15)	0.13 (0.16)	0.06 (0.05)	0.02 (0.04)	0.01 (0.03)	0.02 (0.04)	0.52 (0.30)
201-250	0.00 (0.00)	0.00 (0.00)	0.02 (0.04)	0.00 (0.00)	0.01 (0.03)	0.02 (0.04)	0.02 (0.07)	0.01 (0.03)	0.00 (0.00)	0.09 (0.14)
251-300	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.07 (0.07)	0.02 (0.04)	0.02 (0.07)	0.00 (0.00)	0.00 (0.00)	0.11 (0.08)
> 300	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.02 (0.04)	0.02 (0.04)	0.02 (0.04)	0.00 (0.00)	0.01 (0.03)	0.00 (0.00)	0.08 (0.10)
Total	3.52 (1.20)	17.04 (2.78)	9.76 (1.83)	4.53 (0.98)	1.77 (0.53)	0.71 (0.38)	0.40 (0.32)	0.21 (0.13)	0.08 (0.08)	38.02 (5.54)

Table 3.3. Number of impacts, grouped into classes of peak-acceleration and velocity-change, given for the Phase Transport in the handling-chain: shovelling and truck loading at the farm (standard deviation of the average for the participating growers).

Peak-acceleration class (g)	Velocity-change class (m s ⁻¹)								Total	
	0.0-0.5	0.6-1.0	1.1-1.5	1.6-2.0	2.1-2.5	2.6-3.0	3.1-3.5	3.6-4.0		> 4.0
30- 50	2.56 (1.90)	10.81 (2.48)	4.08 (1.29)	1.38 (0.55)	0.56 (0.34)	0.28 (0.17)	0.11 (0.12)	0.02 (0.04)	0.03 (0.07)	19.82 (4.83)
51-100	0.28 (0.33)	3.10 (1.29)	4.08 (1.05)	2.42 (0.86)	1.07 (0.33)	0.51 (0.25)	0.23 (0.19)	0.12 (0.07)	0.11 (0.14)	11.91 (3.17)
101-150	0.00 (0.00)	0.28 (0.48)	0.46 (0.51)	0.49 (0.32)	0.58 (0.75)	0.23 (0.22)	0.06 (0.08)	0.07 (0.10)	0.03 (0.07)	2.20 (1.36)
151-200	0.00 (0.00)	0.00 (0.00)	0.11 (0.20)	0.13 (0.09)	0.04 (0.05)	0.05 (0.07)	0.03 (0.05)	0.00 (0.00)	0.02 (0.04)	0.38 (0.29)
201-250	0.00 (0.00)	0.00 (0.00)	0.02 (0.06)	0.03 (0.09)	0.01 (0.03)	0.01 (0.03)	0.01 (0.03)	0.01 (0.03)	0.00 (0.00)	0.08 (0.14)
251-300	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.08 (0.29)	0.03 (0.05)	0.02 (0.04)	0.02 (0.06)	0.00 (0.00)	0.00 (0.00)	0.14 (0.29)
> 300	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.03 (0.05)	0.03 (0.06)	0.03 (0.09)	0.00 (0.00)	0.01 (0.03)	0.09 (0.17)
Total	2.83 (2.10)	14.19 (3.67)	8.74 (2.07)	4.53 (1.27)	2.30 (1.07)	1.12 (0.49)	0.49 (0.33)	0.21 (0.13)	0.20 (0.20)	34.62 (8.93)

Table 3.4. Number of impacts, grouped into classes of peak-acceleration and velocity-change, given for the Phase Packaging in the handling-chain: truck unloading, first interim storage, grading, second interim storage, washing, third interim storage and packaging (standard deviation of the average for the participating centres).

Peak-acceleration class (g)	Velocity-change class (m s ⁻¹)									Total
	0.0-0.5	0.6-1.0	1.1-1.5	1.6-2.0	2.1-2.5	2.6-3.0	3.1-3.5	3.6-4.0	> 4.0	
30- 50	27.13 (11.57)	90.13 (8.80)	23.53 (5.67)	9.13 (2.64)	3.93 (1.63)	1.80 (0.70)	0.80 (0.40)	0.50 (0.35)	0.07 (0.06)	157.03 (16.00)
51-100	1.07 (0.51)	30.03 (4.38)	31.03 (1.85)	13.43 (1.27)	6.93 (0.59)	2.80 (1.35)	1.33 (0.23)	0.70 (0.66)	0.83 (0.75)	88.17 (4.06)
101-150	0.03 (0.06)	0.40 (0.26)	4.10 (1.06)	4.00 (2.52)	2.27 (0.76)	1.17 (0.49)	0.40 (0.52)	0.23 (0.32)	0.53 (0.23)	13.13 (4.11)
151-200	0.00 (0.00)	0.03 (0.06)	0.63 (0.25)	1.40 (0.89)	1.00 (0.10)	0.73 (0.45)	0.17 (0.12)	0.03 (0.06)	0.07 (0.06)	4.07 (1.52)
201-250	0.00 (0.00)	0.00 (0.00)	0.03 (0.06)	0.43 (0.31)	0.40 (0.26)	0.43 (0.21)	0.13 (0.15)	0.00 (0.00)	0.07 (0.12)	1.50 (0.10)
251-300	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.10 (0.00)	0.20 (0.10)	0.20 (0.10)	0.13 (0.06)	0.10 (0.17)	0.00 (0.00)	0.73 (0.06)
> 300	0.00 (0.00)	0.00 (0.00)	0.03 (0.06)	0.00 (0.00)	0.00 (0.00)	0.27 (0.12)	0.30 (0.10)	0.30 (0.17)	0.03 (0.06)	0.93 (0.29)
Total	28.23 (12.00)	120.60 (8.80)	59.37 (2.81)	28.50 (1.00)	14.73 (2.14)	7.40 (1.87)	3.27 (1.07)	1.87 (0.98)	1.60 (0.96)	265.57 (14.41)

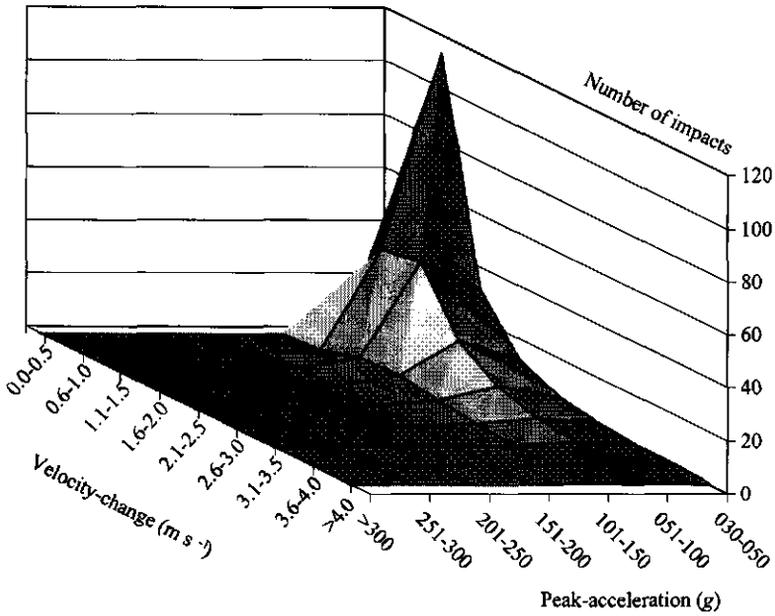


Figure 3.5. Number of impacts, grouped into classes of peak-acceleration and velocity-change, cumulated over four phases in the handling-chain (from lifting through packaging).

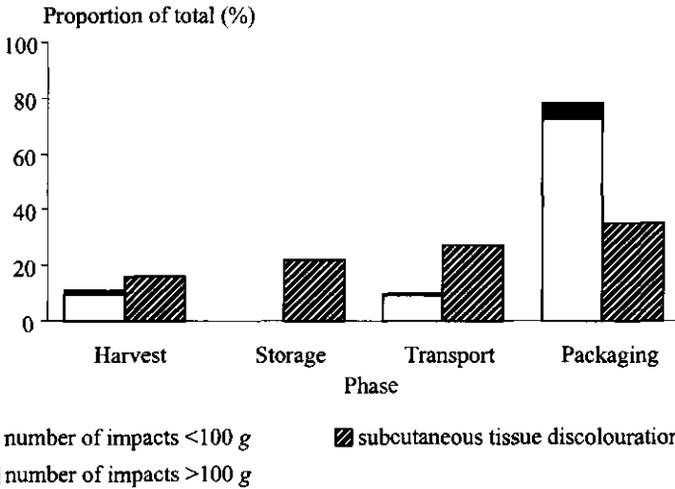


Figure 3.6. Proportion of number of impacts < 100 g, proportion of number of impacts > 100 g and proportion of subsequent subcutaneous tissue discolouration for the four phases in the handling-chain.

of the number of impacts exceeding 100 g and the proportions of subcutaneous tissue discolouration are presented for the four phases in the handling-chain. In the Phases Harvest and Transport the relative occurrence of subcutaneous tissue discolouration exceeded the relative number of impacts. The reverse was observed in the Phase Packaging. For the Phases Transport and Packaging we found for the relationship between the logarithm of the cumulative peak-acceleration and the cumulative index for subcutaneous tissue discolouration an R^2 of 0.95 (range 0.90-0.99; $n = 12$) (Molema & Bouman, 1995).

Discussion

Impact reference measurements

The impact reference measurements are useful to classify impacts recorded in the handling-chain. In this way relative levels of exposure to impact in different phases of the handling process can be identified and translated to probability of true subcutaneous tissue discolouration. Due to the physical properties of the IS, such as weight, size and elasticity, the effect of the IS may differ from that of tubers. Compared to the IS, tubers absorb more energy due to their higher elasticity. Moreover, in Dutch ware-potato handling-chains tubers are usually lighter and smaller than the IS. Therefore penetration of the tubers into the material they impact and the resulting peak-acceleration will be less, compared to impacts caused by the IS.

Impact measurements

Measuring technique. Impacts were recorded by the IS as it moved along with potatoes. In this way rolling of the IS and thus an overestimation of the number of impacts was limited.

Damage threshold. Although damage threshold values for different cultivars at different conditions are not yet established (see *Research needs*), the present results and those of Molema *et al.* (1999) show that in many cases, transfers cause subcutaneous tissue discolouration. Hyde *et al.* (1992) reported that impacts above 100 g have more potential to cause damage than impacts below 50 g.

Mathew & Hyde (1992) reported zero-damage for 250 ± 50 gram Russet Burbank tubers onto a steel plate at drop heights of 25, 30 and 50 mm (corresponding to a peak-acceleration of 69, 81 and 122 g) at tuber temperatures of 10, 15.5 and 21 °C, respectively. Covering with 6.3 mm Poron™ 15250 increased allowable heights for zero-damage to 200, 225 and 250 mm (corresponding to a peak-acceleration of 97, 110 and 122 g), respectively, for the three temperatures.

Number of impacts. The number of impacts recorded (*ca* 340) is high and considerably higher than the number of identified drops (72, Molema *et al.*, 1999) because of

Chapter 3

IS-tuber contacts, IS-machine contacts (e.g. during grading and washing) and by the physical properties ('bouncing') of the IS. As a consequence of the latter, the number of impacts is probably over-estimated compared to that of tubers.

Static load. As reported before static load (pressure) can also lead to subcutaneous tissue discolouration. The IS was not suitable to measure static load. Therefore effects of static load on subcutaneous tissue discolouration in potatoes, e.g. during short-term bunker storage and long-term storage, are not discussed in this chapter.

Repetitive impacts. Due to the large number of impacts and the eccentric position of the centre of gravity in a tuber, tubers may be impacted several times at the same site. The effect of repetitive impacts (at the same tuber site) below the damage threshold on subcutaneous tissue discolouration may be considerable (Molema *et al.*, 1997a).

Impact body shape. Impacts are caused by impact bodies of different shape. For instance the potato harvester is equipped with sieving webs containing rod bars, while tubers can also be impacted by the flat steel plate wall of bunkers. This effect could not be recorded by the IS due to its low elasticity, but the effect of shape on subcutaneous tissue discolouration can be considerable (Molema *et al.*, 1997b).

Impact energy. The recorded impacts belong to the category imperfect elastic impacts; $-0 < e < 1$ - where e = coefficient of impact (Sitkei, 1986). It could further the insight into the relation between impact and subcutaneous tissue discolouration if all impacts could be expressed in terms of energy transfer (in Joules). Therefore drop velocities are required. However, velocity (v) can not be derived from the impact data. Therefore it is impossible to calculate the impact energy.

Impact measurements and subcutaneous tissue discolouration

In the Phase Transport impacts caused relatively more subcutaneous tissue discolouration than in the Phase Harvest. This may be a consequence of a higher susceptibility to subcutaneous tissue discolouration, probably induced by a low ambient temperature (Molema *et al.*, 1999). In the Phase Packaging a high number of impacts was associated with relatively little subcutaneous tissue discolouration. An explanation for this effect could be that the more subcutaneous tissue discolouration potatoes obtain, it is less likely that the subcutaneous tissue discolouration will increase further until potatoes are entirely discoloured. Due to the cumulative effect the absolute increase of subcutaneous tissue discolouration may be underestimated towards the end of the chain. In contrast to the results of the Phase Packaging (Figure 3.6) impacts may increase the amount of subcutaneous tissue discolouration substantially because in the present study potato samples were only assessed for subcutaneous tissue discolouration on the surface after peeling. Molema *et al.* (1997a, b) showed that the depth of discoloured tissue also has to be considered.

Herold & Habelt (1992) reported a correlation between potato damage and the accumulated load index measured by means of a pressure measuring sphere. According to Sober *et al.* (1989) varying the peak-acceleration level had most effect on the

average bruise diameter.

Research needs

Initiation of subcutaneous tissue discolouration strongly depends on the type, intensity and frequency of impacts, but is also influenced by factors like tuber temperature, turgidity, variety, dry matter content, *etc.*. Therefore tissue discolouration resistance is variable (Hyde *et al.*, 1993), also within the same lot (Molema *et al.*, 1997a; Veerman *et al.*, 1996). Consequently, it is rather complicated to derive a generally valid subcutaneous tissue discolouration threshold. Additional research is needed that will help to understand impact conditions that may result in subcutaneous tissue discolouration in potato tubers (damage threshold). Next to that, subcutaneous tissue discolouration accumulation due to repetitive impacts (Molema *et al.*, 1997a) and the effect of impact body shape (Molema *et al.*, 1997b) has to be studied.

So far, the effect of repetitive impacts and impact body shape were studied separately. However in practice the different types of impacts may have a synergetic effect. Since the effect is not quantified yet, additional experiments are needed to predict the probability of subcutaneous tissue discolouration in handling-chains.

Practical implications

The number and intensity of the impacts recorded in this study were too large. Optimal utilization of technique and technology, *e.g.* fewer drops, accumulation of tubers on certain sites in the handling-chain (Hyde *et al.*, 1990), *etc.* is crucial to limit impacts in number and intensity (Molema *et al.*, 1999). Good cushioning material (*e.g.* the rubber foam tested) will absorb more of the impact energy, and spread the impact over a longer period of time, thus reducing the subcutaneous tissue discolouration potential. Belting on steel (*e.g.* the PVC) provides very little cushioning effect (Figure 3.4). In the Phase Packaging (truck unloading through packaging) *ca* 80% of the impacts in the entire chain occurred. Probably in this phase subcutaneous tissue discolouration can be reduced seriously by improvement of the handling technology with respect to produce-friendliness. In this way it is expected that especially the depth of discoloured tissue can be reduced drastically.

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CHAPTER 4

A computer-controlled pendulum to impact potato tubers precisely

Abstract

An analysis of representative Dutch ware-potato handling-chains showed that 78% of the total amount of subcutaneous tissue discolouration was caused by impacts. Instrumented sphere measurements showed that tubers were impacted frequently. To study the effect of different types of impacts a new computer-controlled pendulum was developed by which the impacts that potatoes experience in practice could be simulated. The system configuration consists of a pendulum, an interface and a computer. The pendulum-device proved to be an adequate tool to impact tubers precisely and reproducibly. Moreover the configuration provided accurate records of the impact history. The pendulum can be instrumental in studying the relations between impact and subcutaneous tissue discolouration in detail, particularly in visco-elastic produce.

Keywords: blackspot, bruising, handling, impact, impact body, internal damage, pendulum, potato, subcutaneous tissue discolouration, visco-elastic produce

Introduction

On their way from the field to the consumer potato tubers are exposed to many short-time mechanical forces (impacts) and to pressure. Impacts and pressure can lead to subcutaneous tissue discolouration (Molema *et al.*, 1999a, b). An analysis of representative Dutch ware-potato handling-chains (Molema *et al.*, 1999a) showed that 78% of the total amount of subcutaneous tissue discolouration was caused by impacts. Instrumented sphere measurements (Molema *et al.*, 1999b) in such chains showed that, on average *ca* 340 impacts exceeded 30 g. Molema *et al.* (1999b) found that 88% of the total number of recorded drop heights was in the category 0-60 cm. Hyde *et al.* (1992) reported that impacts above 100 g have more potential to cause subcutaneous tissue discolouration than impacts below 50 g. For apple, damage thresholds of 30-50 g have been reported (Tennes *et al.*, 1988; Sober *et al.*, 1989). From the impact data different types of drops could be distinguished according to the corresponding peak-acceleration and velocity-change (Molema *et al.*, 1999b). Although of scientific and practical interest the effect of impacts of different types, *e.g.* different impact body shapes, the effect of a sequence of impacts at the same site of the tuber and the effect of intervals between consecutive impacts on subcutaneous tissue discolouration are not known. To study these effects, there is a need for a method to simulate impacts that

potatoes experience in practice. This chapter presents a method to impact tubers precisely at a desired rate.

Different dynamic methods inflicting subcutaneous tissue discolouration can be distinguished. Based on literature data we assessed the characteristics of the various impact techniques (Table 4.1) and selected a pendulum as the most promising principle. A pendulum offers the possibility to obtain detailed information about the pre-impact, the impact and the post-impact events. The principle of a pendulum also offers the possibility to arrest the pendulum arm when it comes to a standstill after

Table 4.1. Characteristics of different impact techniques.

Technique	Characteristic										
	Site specific impacts	Repetitive impacts	Sample holding system ^A	Different impact bodies (e.g. weight, shape)	Different impact surfaces (e.g. elasticity)	Pre-impact, impact and post-impact data-control (acceleration, velocity, time)	Correction for friction and air resistance	Fixation after rebound	Computer control of data processing	Precision	Simple and fast
Falling potato ¹	-	-	+	-	+	-	-	-	-	-	+
Simulated handling ²	-	-	-	-	±	-	-	-	-	-	+
Falling mass ³	-	-	+	+	-	-	-	-	-	-	+
Tube-guided falling mass ⁴	+	±	±	+	±	±	-	-	±	±	±
Potato thumper ⁵	+	+	-	+	-	±	-	-	-	-	±
Pendulum ⁶	+	±	+ ^B	+	-	±	±	±	±	+	±

^A some sample holding systems can damage potatoes.

^B potatoes are often held under static load.

¹ McRae, 1978; Volbracht & Kuhnke, 1956.

² Ophuis *et al.*, 1958; Pavek *et al.*, 1985; Skrobacki *et al.*, 1989; Wiant *et al.*, 1951.

³ Volbracht & Kuhnke, 1956; Weaver & Steen, 1966; Witz, 1954.

⁴ Chen *et al.*, 1987; Fluck & Ahmed, 1973; Garcia *et al.*, 1988; Howard *et al.*, 1961; Johnson, 1972; Kunkel & Gardner, 1959; Kunkel *et al.*, 1986; Maas, 1966; Pavek *et al.*, 1985; Sawyer & Collin, 1960; Schippers, 1971; Wright & Splinter, 1968.

⁵ Skrobacki *et al.*, 1989.

⁶ Gall *et al.*, 1967; Grant & Hughes, 1985; Hughes *et al.*, 1975; Hung & Prussia, 1989; Nerinckx, 1993; Noble, 1985; Parke, 1963; Skrobacki *et al.*, 1989.

+ characteristic present, - characteristic absent, ± characteristic sometimes present/sometimes absent.

impact, so undesired repetitive impacts can be avoided. For our goal the pendulum has to meet the following specifications:

- simulate drops (up to *ca* 60 cm) that average potatoes undergo in practice;
- allow a stable positioning of the flat back of longitudinally-cut potatoes (sample holding system);
- allow displacement in all directions of the sample holding system in order to be fixed precisely before impact;
- changeable impact body to permit the use of different shapes and masses;
- no external damage after impact allowed;
- impact tubers precisely and reproducibly;
- exactly control and measure velocity just before impact, acceleration and delivery and absorbance of energy;
- register acceleration by means of an acceleration/time curve so that impact duration and the change in velocity can be recorded;
- deliver the predetermined impact energy and the corresponding velocity just before impact with a maximum inaccuracy of 5%; a wider range must be avoided because of the additional effect on inaccuracy of natural variation in subcutaneous tissue discolouration within tuber lots;
- computer-controlled data processing.

Current pendula were not able to meet all these specifications. Therefore a new computer-controlled pendulum-device was designed in which different aspects of other pendula were taken into account. This chapter describes the design, use, accuracy tests and applicability of the new pendulum.

Experimentation

Pendulum design

Background. Physically there is no difference between a potato with mass m_1 free-falling from height h_1 impacting an inelastic mass and a potato which is impacted by a pendulum with an inelastic mass m_2 [effective mass of impact arm (m_a) and impact body (m_b)], provided the falling mass m_2 is equal to the potato mass m_1 and the height h_2 is equal to h_1 (Figure 4.1). For the situations presented in Figure 4.1 there is no difference in potential energy (E_{pot}) and the contact velocity v_1 (velocity just before impact), where $v_1 = \sqrt{2 g h}$ in which g is acceleration due to earth's gravity (9.81 m s^{-2}) and h is drop height. Impact energy is determined by the initial angle (α) of the pendulum arm, 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. In this approach corrections for air-resistance and friction are not taken

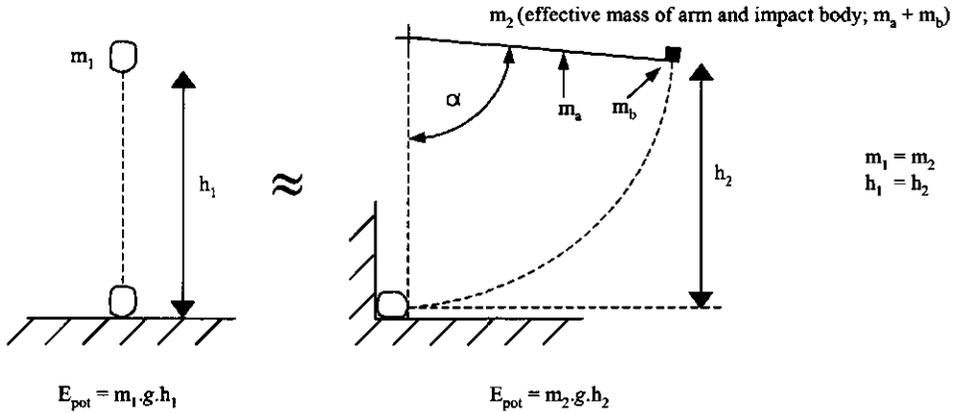


Figure 4.1. Schematic representation of a falling potato (L) and a simulation of a falling potato with a pendulum (R).

into account.

System configuration. The computer-controlled pendulum configuration is shown schematically in Figure 4.2. The main parts of the configuration are the pendulum mainframe including pendulum arm and sample holding system, an interface and a computer. The initial angle of the arm before impact is represented as α , β represents the rebound angle of the arm after impact.

Mainframe and pendulum arm. The mainframe (Figure 4.3) is constructed triangularly and has to be solidly anchored. The pendulum arm is a conic carbon fibre tube with an effective length and an average diameter of 600 and 16.4 (range 14.5-18.2) mm, respectively. At the top of the mainframe the arm is suspended by means of a pivot in two precision ball-bearings with a very low coefficient of friction. In the critical measuring range vibration of the pendulum arm is avoided.

Impact body. Three impact bodies were developed: a non-spherical [radius of curvature (r.o.c.) ∞] and two spherical impact bodies (r.o.c. 30 and 15 mm) referred to as B_∞ , B30 and B15, respectively (Figure 4.4). The shape of the impact bodies is based on the range of shapes of impacting surfaces used in potato handling systems. The impact body diameter was 30 mm.

Effective mass. Following the schematic representation of Figure 4.1 the effective mass (m_2) of the pendulum arm (m_a ; accelerometer cable included) and impact body (m_b ; accelerometer included) has to be 120 g (average weight of potatoes, cv. Bintje, grade 50-60 mm; Molema *et al.*, 1999a). According to F.H. Fockens (pers. comm.) the weight of the impact body (m_b) is defined as:

$$m_b = m_1 - 1/3m_a \quad (4.1)$$

and h_2 is defined as:

$$h_2 = h_1 \cdot m_1 / (m_1 + 1/6m_a) \quad (4.2)$$

where h_1 (Figure 4.1) is 0.6 m, m_1 is 120 g and m_a is 46.92 g.

Rotary encoder. At the top of the mainframe the pivot is equipped with an opto-electronic incremental position rotary encoder. In one rotation (360°) the rotary encoder produces 2,500 pulses. Rotation of the arm requires $5 \cdot 10^{-3}$ Nm due to the rotary encoder friction.

Electromagnetic coupling. The pivot at the top of the mainframe can be fixed by an electromagnetic coupling in each position of rotation. Fixation of the arm is necessary to administer the potential impact energy (E_{pot}) and to keep the arm in its highest position after rebound.

Accelerometer. At the backside of the impact body the pendulum arm is equipped with an accelerometer with a 0-500 g measuring range (non-linearity 1%) and a 0-5,700 Hz frequency range. The accelerometer measures the deceleration during impact and acceleration of the impacting mass after impact.

Sample holding system. In contrast to other pendula (e.g. Grant & Hughes, 1985) tubers were not held under a static load to prevent movement, but a passive sample holding system was constructed. The sample holding system is movable and adjustable. It both can be moved along the x-, y- and z-axis and rotated around z-axis (R_z) by means of a spindle (z-axis) and an electromagnet (x-, y-axis and R_z) (Figure 4.3). The construction enables a very precise positioning of the potato piece. Cut potatoes with a thickness of ca 30 mm were used (Molema *et al.*, 1997a, b). Cutting potatoes into pieces allows a stable positioning of the flat back of the pieces onto the

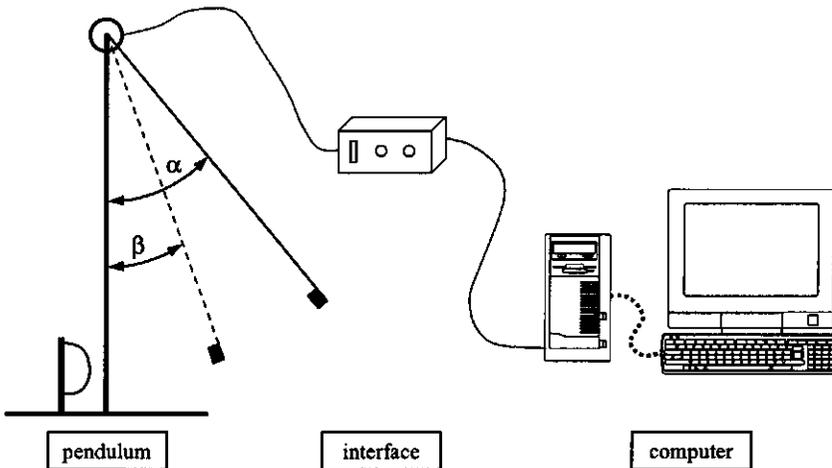


Figure 4.2. Configuration of the computer-controlled pendulum.

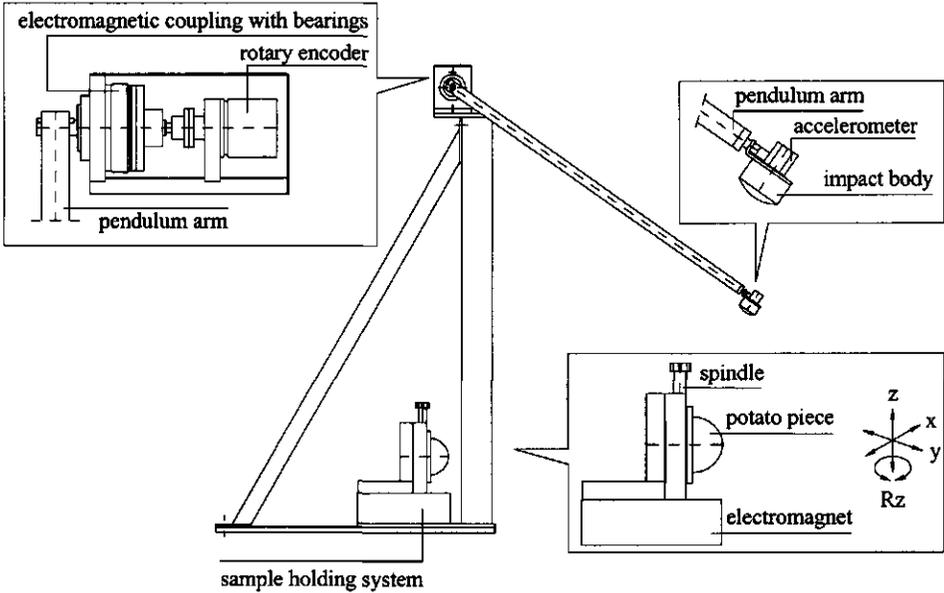


Figure 4.3. Schematic drawing of the pendulum-device.

backplate of the holding system. Finney (1963) found no difference between the effect of impacts on whole and halved tubers. The tuber pieces were arrested by means of two pins extending 12 mm (diameter 1 mm).

Computer

Impact characterization. To characterize the impact curve at least 50 measurements were taken. The minimum impact duration (non-spherical impact body) for the potatoes used was *ca* 3 ms.

Crystal oscillator. The time keeping frequency of the crystal oscillator is 1 MHz with an instability of $1 \cdot 10^{-5} f$. The oscillator is equipped with a 16 bits counter (65,535 counts).

Software. A computer program for operating and controlling the pendulum was developed in Visual Basic for DOS from Microsoft.

Experimental conditions

During impact experiments temperature may vary between 5 and 30 °C due to the thermal stability of the measuring equipment. To prevent changes in air resistance, an air jet in the surroundings of the pendulum is not allowed. For tuber and ambient temperature selected see section *Experiment*.

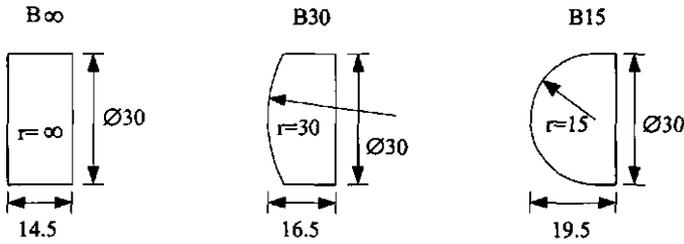


Figure 4.4. Schematic drawing of the impact bodies (dimensions in mm).

Operation and control

To impact a tuber at a desired rate the level of potential energy (E_{pot} : the selected potential impact energy) has to be entered into the computer. The required angle of the pendulum arm necessary to deliver the E_{pot} is calculated by the computer. This selected value may deviate somewhat from the real level of potential energy (real potential impact energy, see Table 4.2). This procedure allows for air-resistance and friction. At the start of the impact protocol, the pendulum arm has to be positioned in the lowest point of its oscillation after which the position is registered by the computer. The potato piece has to be fixed into the sample holding system and positioned so that the impact body at the end of the pendulum arm at the lowest point of its oscillation faces the sample at a marked impact site. The pendulum arm is lifted manually to the required position at the initial angle α (Figure 4.2) where it is arrested (computer controlled) by the electromagnetic coupling. By a computer command the pendulum arm is released to free-fall. At 55 μs intervals measurements take place of the position, time, deceleration and acceleration of the pendulum arm. Measurements are continued up to ca 10 ms after impact. An impact was defined as follows: when the deceleration of the pendulum arm exceeds 5 g the impact starts, when the acceleration of the pendulum arm decreases below 5 g the impact is finished. Data storage is limited to the last 600 measurements.

The pendulum arm is automatically arrested when it has come to a standstill after rebound from an impact. From the rebound angle (β) the non-absorbed energy can be calculated (accuracy ca 2 mJ). Finally the computer calculates the real potential impact energy, the energy absorbed, velocity just before impact, duration of impact, maximum acceleration (maximum deceleration of the arm), duration from starting the impact till the time of maximum deceleration and the velocity just after impact. Together with information like tuber number and impact number, these data are stored.

Chapter 4

Checks

Instrument check

The pendulum is equipped with three measuring instruments: a rotary encoder, an accelerometer and a crystal oscillator.

Rotary encoder. Drop height is calculated according to the following equation:

$$h_2 = m_L \cdot (1 - \cos \alpha) \quad (4.3)$$

where m_L is the length of the pendulum arm and α is the initial angle (Figure 4.1). When $\alpha = 0^\circ$ corresponding with a drop height of 0 cm the resolution is 2 μm ; when $\alpha = 90^\circ$ corresponding with a drop height equivalent to the length of the arm (600 mm) the resolution is 1.5 mm. The latter resolution represents the distance between the consecutive pulses of the rotary encoder.

Accelerometer and crystal oscillator. The accelerometer and crystal oscillator were calibrated by the manufacturer.

System check

Calibration of the whole system is possible by combining the three instruments the system is equipped with. By combining the data obtained from the rotary encoder and the crystal oscillator the velocity before impact (v_1) can be calculated; velocity after impact (v_2) is calculated from the rebound angle (β) of the pendulum arm. Data recorded by the accelerometer offer the possibility to calculate $\int a \, dt$ where a is acceleration and t is time. In a precise measuring system this gave the following equation:

$$v_1 + v_2 = \int a \, dt \quad (4.4)$$

Calculations are carried out by a computer program. The maximum allowable deviation (in %) between $v_1 + v_2$ and $\int a \, dt$ can be entered and a warning will be given when the deviation is exceeded.

Experiment

The tubers (*Solanum tuberosum* L. cv. Bintje, grade 50-60 mm) were produced, harvested and stored (3 months) as described by Molema *et al.* (1997a). The experiments were done at 10 °C. The tubers were transferred to 10 °C and 93% RH ca 1 week prior to impact experiments. Potatoes were cut longitudinally into pieces with a thickness of 30 ± 2 mm.

Verification of accuracy. The accuracy of the pendulum was checked for the variables real potential impact energy, velocity just before impact, and the real impact energy calculated from the velocity just before impact according to the following equation:

$$1/2m_2 v_1^2 \quad (4.5)$$

where m_2 is the effective mass of the pendulum arm and impact body ($m_a + m_b$; Figure 4.1) and v_1 the velocity just before impact.

The experiment comprised nine treatments which were combinations of impact energy (0.6, 0.2 or 0.067 J) and impact body shape (r.o.c. ∞ , 30 or 15 mm). Per treatment 45 tubers were impacted and measurements were done.

Potato impact characteristics. Reproducibility of impact measurements for peak-acceleration and duration was investigated by impacting 45 tubers per treatment.

Data processing. The measurements per treatment were averaged ($n = 45$) and standard deviations were calculated.

Results

Accuracy

Real potential impact energy. The real potential impact energy deviated little from the adjusted impact energy (set values) (Table 4.2). On average, deviation for the different combinations of energy treatment and impact body shape ($n = 9$) ranged from +0.3 to +0.7 %, relative to the set values. Minimum and maximum deviation were 0 and 3%, respectively. The average deviation increased with decreasing impact energy.

Impact velocity. The measured impact velocity deviated also little from the calculated impact velocity (Table 4.3). On average, deviation for the different combinations of E_{pot} and impact body shape ($n = 9$) ranged from -1 to +4%. The average deviation increased with a decreasing impact energy. Minimum and maximum deviation were -2 and +4%, respectively.

Table 4.2. Real potential impact energy (J) at three set potential energy (E_{pot} in Joule) treatments and three impact body shapes (B ∞ , B30, B15). Standard deviation given in parenthesis, $n = 45$.

Impact body	E_{pot} (J)		
	0.600	0.200	0.067
B ∞	0.602 (0.001)	0.201 (0.001)	0.067 (0.001)
B30	0.602 (0.001)	0.201 (0.001)	0.067 (0.000)
B15	0.602 (0.001)	0.201 (0.001)	0.067 (0.001)

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Table 4.3. Measured impact velocity (m s^{-1}) at three set potential energy (E_{pot} in Joule) treatments and three impact body shapes (B_{∞} , B30, B15). Theoretical velocities were calculated for each E_{pot} . Standard deviation given in parenthesis, $n = 45$.

Impact body	Theoretical velocity (m s^{-1})		
	3.164 ($E_{\text{pot}} = 0.600$)	1.827 ($E_{\text{pot}} = 0.200$)	1.057 ($E_{\text{pot}} = 0.067$)
B_{∞}	3.160 (0.050)	1.820 (0.040)	1.100 (0.000)
B30	3.116 (0.037)	1.833 (0.048)	1.100 (0.000)
B15	3.144 (0.050)	1.844 (0.050)	1.100 (0.000)

Table 4.4. Real impact energy (J) at three set potential energy (E_{pot} in Joule) treatments and three impact body shapes (B_{∞} , B30, B15). Standard deviation given in parenthesis, $n = 45$.

Impact body	E_{pot} (J)		
	0.600	0.200	0.067
B_{∞}	0.599 (0.019)	0.199 (0.009)	0.073 (0.000)
B30	0.582 (0.014)	0.202 (0.011)	0.073 (0.000)
B15	0.593 (0.019)	0.204 (0.011)	0.073 (0.000)

Real impact energy. Deviation for the different combinations of E_{pot} and impact body shape ($n = 9$) ranged from -3 to +8%, on average (Table 4.4). The average deviation increased with a decreasing real impact energy. Minimum and maximum deviation were -4 and +8%, respectively.

Potato impact characteristics

Spherical impact bodies gave a lower peak-acceleration and a longer impact duration, relative to the flat impact body (Table 4.5). Variation in impact characteristics within treatments was small. The difference between impact characteristics of the two spherical impact bodies (B30 and B15) was small (for details see Molema *et al.*, 1997b).

Table 4.5. Acceleration (g) and impact duration (ms) at three potential energy (E_{pot} in Joule) treatments and three impact body shapes (B ∞ , B30, B15). Standard deviation given in parenthesis, $n = 45$.

Impact body		E_{pot} (J)		
		0.600	0.200	0.067
B ∞	g	286.9 (14.2)	159.2 (10.4)	81.4 (7.6)
	ms	2.85 (0.12)	3.03 (0.16)	3.30 (0.21)
B30	g	237.0 (9.6)	132.1 (5.7)	69.5 (4.7)
	ms	3.36 (0.09)	3.55 (0.15)	3.74 (0.17)
B15	g	224.2 (5.7)	120.5 (6.7)	64.3 (3.56)
	ms	3.51 (0.10)	3.81 (0.17)	4.00 (0.13)

Discussion

Pendulum-device

Utilization. The pendulum-device that we designed proved to be an adequate tool to study effects of impacts on subcutaneous tissue discolouration (damage) under the specifications given in the introduction. Parallel with the development of the pendulum presented in this chapter, Baheri (1997) developed a pendulum according to the principle described in this chapter; in that case potatoes were fixed by a simple wide elastic rubber band.

Restrictions. Disadvantage of the pendulum-device is that before impact the pendulum arm has to be lifted manually. This procedure to start an impact can be automated. It could also be useful to create facilities to measure penetration during impact and to study the effect of tuber-tuber impacts.

Rebound velocity. Due to vibration and bending of the pendulum arm after impact, the rotary encoder measurements can be inaccurate. Therefore rebound velocity was calculated from the rebound height.

Sample holding system. A passive sample holding system (without external forces) was used to prevent tubers from a static load before, during and after impact. Disadvantage of this sample holding system is that potatoes have to be cut longitudinally. The use of cut tubers had the advantage that differences in radius of curvature of the (backside of the) tuber and in the surface of the contact area between tubers and the sample holding system did not affect the results. Other sample holding techniques could be a potato, freely suspended by threads (Parke, 1963), a hand held tuber (Maas, 1966), using rubber wedges (Kunkel & Gardner, 1959) or using modelling clay (Hung & Prussia, 1989).

Reproducibility and accuracy

Impact energy and impact velocity. The administration of the real potential impact energy and the velocity just before impact could be accurately and reproducibly controlled. The achieved values for the two parameters complied with the pre-defined accuracy of *ca* 5% relative to the theoretical value. Deviation of the set impact energy could be accounted for by the time lapse between signalling the desired position of the arm and arresting of the arm. Deviation of the measured velocity from the theoretical velocity just before impact may be accounted for by the deviation in arresting height of the arm and by air-turbulence around the pendulum arm. Deviation of the real impact energy, calculated from the velocity just before impact, according to equation 4.5, exceeds at low impact energy treatments, the predefined accuracy of 5% relative to the set values. This inaccuracy is caused by the fact that data are saved with only one decimal.

Produce-related effects. Variation of impact characteristics within treatments was small and is probably caused by the tuber firmness and radius of curvature of the impact site of the tuber (Noble, 1985; Molema *et al.*, 1997b).

Conclusions

The new developed pendulum-device proved to be an adequate tool to impact tubers precisely and reproducibly at a desired rate (simulate drops that average potatoes undergo in practice). The changeability of the impact body permits the use of different shapes, masses and materials. The sample holding system allowed a stable positioning of the cut potatoes and allowed precise displacement into the desired position. Information about the pre-impact, impact and the post-impact events can be revealed in detail. The pendulum is able to exactly control and measure velocity just before impact, acceleration, and delivery and absorbance of energy. The relation between acceleration and time can be presented graphically so that impact duration and the change in velocity can be calculated (Molema *et al.*, 1997b). The accuracy of the administered (theoretical) impact energy and impact velocity was high (> 95%). The real impact energy deviated up to 8%, from the set values. The pendulum is equipped with a warning system concerning measuring accuracy. External damage of tubers was not observed.

Due to its multi-purpose qualities the pendulum is useful to study the relations between impact and subcutaneous tissue discolouration for potato and other produce like apples, peaches, *etc.*. The technique offers the possibility to study the effect of a wide range of impact energy, impact velocity, impact body shape, time intervals between consecutive impacts and their interactions on subcutaneous tissue discolouration.

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CHAPTER 5

Effect of repetitive impacts on subcutaneous tissue discolouration in potato tubers

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

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

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 may be impacted up to 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,

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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 mm) in Sloodorp (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 (K_L) or a high (K_H) 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 K_L and K_H 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 5.1) to impact tubers at a desired rate. The impact energy is determined by the initial angle (α) of the

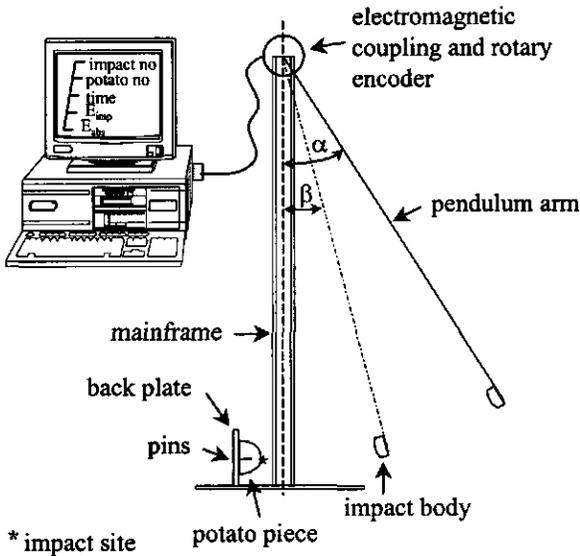


Figure 5.1. Schematic representation of the pendulum-device.

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 computer program compensates for energy losses due to friction at the mainframe-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 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

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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.

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 5.2) and by adding up the number of slices with discoloured tissue. The cross sections of the discoloured tissue were

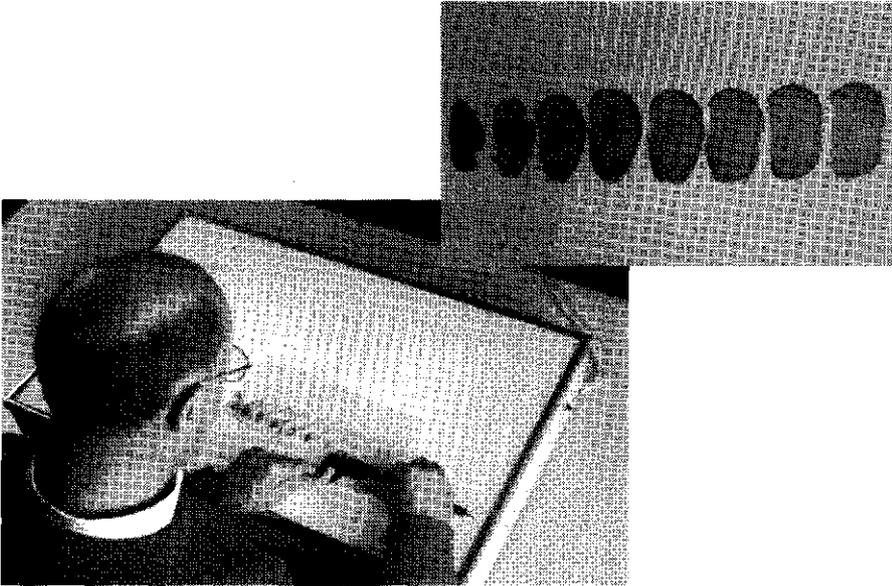


Figure 5.2. Assay of depth and volume of discoloured tissue by analysis of potato slices.

predominantly 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 chapter tissue discoloration 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 discoloration 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 three 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:

$$\log\left(\frac{\gamma_i}{1-\gamma_i}\right) = \sum \theta_i + Xb + Zu \quad (5.1)$$

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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 . The latter term makes the equation (5.1) 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 analyzed. 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 analyzed.

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 generalized 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:

$$\log(y) = Xb \quad (5.2)$$

in which y is the depth of discoloured tissue. These depth data were analyzed 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 analyzed. 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. K_L tubers contained *ca* 2% more DM than K_H tubers (Table 5.1). The susceptibility index for discolouration was positively correlated with the dry matter content. Susceptibility increased during storage up to 5 months, but fell after 7 months (Table 5.1). The average fresh weight (125 ± 29 g), dimensions (length 82 ± 10 mm, width 55 ± 4 mm)

Table 5.1. Dry matter content and susceptibility to discolouration in tubers grown at two potassium levels (K_L , K_H) and stored for 0, 3, 5 or 7 months (0, 3, 5, 7M).

Storage period	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

and radius of curvature of the impact site ($r = 54 \pm 18$ 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 energy delivered by the pendulum-device, independent of storage period (Table 5.2).

Table 5.2. 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

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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 5.2). 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 nine doses reduced the volume of discoloured tissue by 64% on average (Table 5.3). 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 K_L tubers were more damaged than the K_H tubers, the 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 discoloration was less affected (33% reduction on average, Table 5.4) by splitting impact energy into nine doses than the volume of discoloured tissue (64%). The second and sixth value

Table 5.3. Volume of discoloured tissue ($n = 45$) after four impact energy (E_{imp} in J) treatments (Experiment 1) in tubers from plants grown at two potassium levels (K_L , K_H) averaged over three storage periods (upper part of the table) and stored for 3, 5 or 7 months (3, 5, 7M) averaged over two 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
K_L	1020 ^{bC}	707 ^{bB}	359 ^{aA}	366 ^{bA}
K_H	638 ^{aC}	554 ^{aC}	332 ^{aB}	239 ^{aA}
3M	1102 ^{nO}	900 ^{nN}	488 ^{nM}	451 ^{aM}
5M	732 ^{mO}	523 ^{mNO}	393 ^{nMN}	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 5.4. Depth of discoloured tissue ($n = 45$) after four impact energy (E_{imp} in J) treatments (Experiment 1) in tubers from plants grown at two potassium levels (K_L , K_H) 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
K_L	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 ^{kim}	4.1 ^{mn}
K_H	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.

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 5.7). 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 discoloured tissue increased with the number of 0.3 J impacts (Table 5.5). The effect

Table 5.5. Volume of discoloured tissue ($n = 45$) after five impact energy (E_{imp} in J) treatments (Experiment 2) in tubers stored for 3, 5 or 7 months (3, 5, 7M) averaged over two 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.

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Table 5.6. Volume of discoloured tissue ($n = 45$) in tubers from plants grown at two potassium levels (K_L , K_H) and stored for 3, 5 or 7 months (3, 5, 7M) averaged over five impact energy treatments (Experiment 2).

Treatment	Volume of discoloured tissue (mm^3)		
	3M	5M	7M
K_L	1206 ^{bc}	1000 ^{bb}	542 ^{aA}
K_H	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.

varied quantitatively between the various storage periods, but in all cases more impacts caused more damage. Eight times 0.3 J yielded a three to four 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 5.3) comparable impacts resulted in a lower volume of discoloured tissue in material stored for 7 months, as compared to 3 months (Table 5.5). K_L tubers were more damaged than K_H tubers (Table 5.6).

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 5.7). The same tendency was found for the parameter volume of discoloured tissue (Table 5.5).

Table 5.7. Depth of discoloured tissue ($n = 45$) after four impact energy (E_{imp} in J) treatments (Experiment 2) in tubers from plants grown at two potassium levels (K_L , K_H) and stored for 3, 5 or 7 months (3, 5, 7M).

Treatment		Depth of discoloured tissue (mm)				
		E_{imp} (J)				
		1×0.600	1×0.300	2×0.300	4×0.300	8×0.300
K_L	3M	9.3 ^c	6.5 ^{gh}	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 ^j	6.1 ^{efg}	7.2 ^{cd}	8.9 ^b
K_H	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.

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 5.8). As observed before (Experiment 1 and 2) K_L tubers were more damaged than K_H tubers (Tables 5.8 and 5.9).

The interaction term storage period x potassium level had a significant effect on the depth of discoloured tissue (Table 5.10). The depth of tissue discoloration 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.

Table 5.8. Volume of discoloured tissue ($n = 45$) after three impact (E_{imp} in J) treatments (Experiment 3) in tubers from plants grown at two potassium levels (K_L , K_H) averaged over a 3, 5 or 7 months storage period.

Treatment	Volume of discoloured tissue (mm^3)		
	E_{imp} (J)		
	1×0.600	$0.600 + 0.200 + 0.067$	$0.067 + 0.200 + 0.600$
K_L	1038 ^{bb}	909 ^{ba}	926 ^{ba}
K_H	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 5.9. Volume of discoloured tissue ($n = 45$) in tubers from plants grown at two potassium levels (K_L , K_H) and stored for 3, 5 or 7 months (3, 5, 7M) averaged over three impact treatments (Experiment 3).

Treatment	Volume of discoloured tissue (mm^3)		
	3M	5M	7M
K_L	924 ^{bb}	1096 ^{bb}	853 ^{ba}
K_H	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 5.10. Depth of discoloured tissue ($n = 45$) in tubers from plants grown at two potassium levels (K_L , K_H) and stored for 3, 5 or 7 months (3M, 5M, 7M) averaged over three impact treatments (Experiment 3).

Treatment	Depth of discoloured tissue (mm)		
	3M	5M	7M
K_L	8.7 ^a	8.6 ^b	8.1 ^c
K_H	8.2 ^c	7.5 ^c	5.5 ^d

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 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 cm³, 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 5.1). 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 5.2). 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 K_L tubers were more damaged than K_H tubers. The former had a higher DM content (Table 5.1) and DM content is positively related to susceptibility to tissue discolouration (Burton, 1969; Hughes, 1974, 1980; see also Table 5.1). 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 5.4) and an average reduction of the volume of discoloured tissue of 64% (Table 5.3), 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. G. Nerinckx & R. Verschoore (pers. comm.) found a larger reduction (92%) in the volume of tissue discolouration when 0.9 J was divided over three 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 x 0.1 and 9 x 0.067 J was minimal. The difference in absorbed energy after these two impact treatments was also negligible (Table 5.2). 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 5.5 and 5.7). 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. G. Nerinckx & R. 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 5.8 and 5.9). G. Nerinckx & R. 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 absence 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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CHAPTER 6

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

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

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

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 may be impacted up to 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 6.1) 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 thickness of 30 ± 1 mm. Cutting into pieces allowed a stable positioning of the flat back of the pieces to the backplate

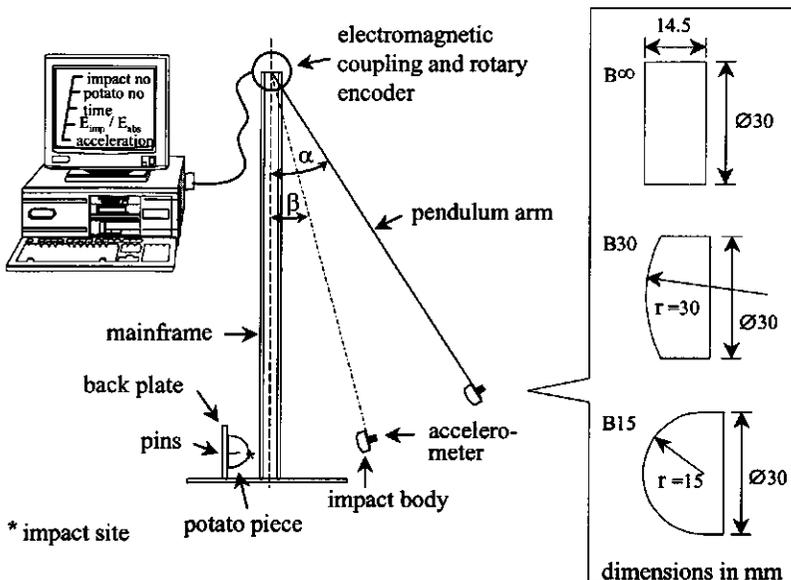


Figure 6.1. Schematic representation of the pendulum-device and the impact bodies.

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. 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. However, 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.

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 two potassium levels (K_L and K_H).

Impact characteristics

Impact characteristics (acceleration *vs* duration) were recorded of the nine treatments of K_H (high level of potassium fertilizer) 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 chapter 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 analyzed 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:

$$\log\left(\frac{\gamma_i}{1-\gamma_i}\right) = \sum \theta_i + Xb + Zu \quad (6.1)$$

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 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 analyzed 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:

$$\log(y) = Xb \quad (6.2)$$

in which y is the depth of discoloured tissue. These depth data were analyzed 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 6.1). 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 6.1).

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 6.2). 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 7 months (Tables 6.3, 6.4 and 6.5). K_L tubers were more damaged by impact than K_H tubers (Tables 6.3, 6.4, 6.5 and 6.6). 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 discoloured 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.

Table 6.1. 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

Table 6.2. Impact energy (E_{imp}) and absorbed energy (E_{abs}) in tubers of nine treatments averaged over two 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 of the mean).

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)

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 6.2). 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 6.3 to 6.6 are experimental means instead of predicted values which were used for the statistical analysis.

Volume of discoloured tissue. The interaction terms impact energy x potassium level and impact energy x 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 6.3).

The interaction terms impact body shape x potassium level and impact body shape x storage duration also had a significant effect on the volume of discoloured tissue.

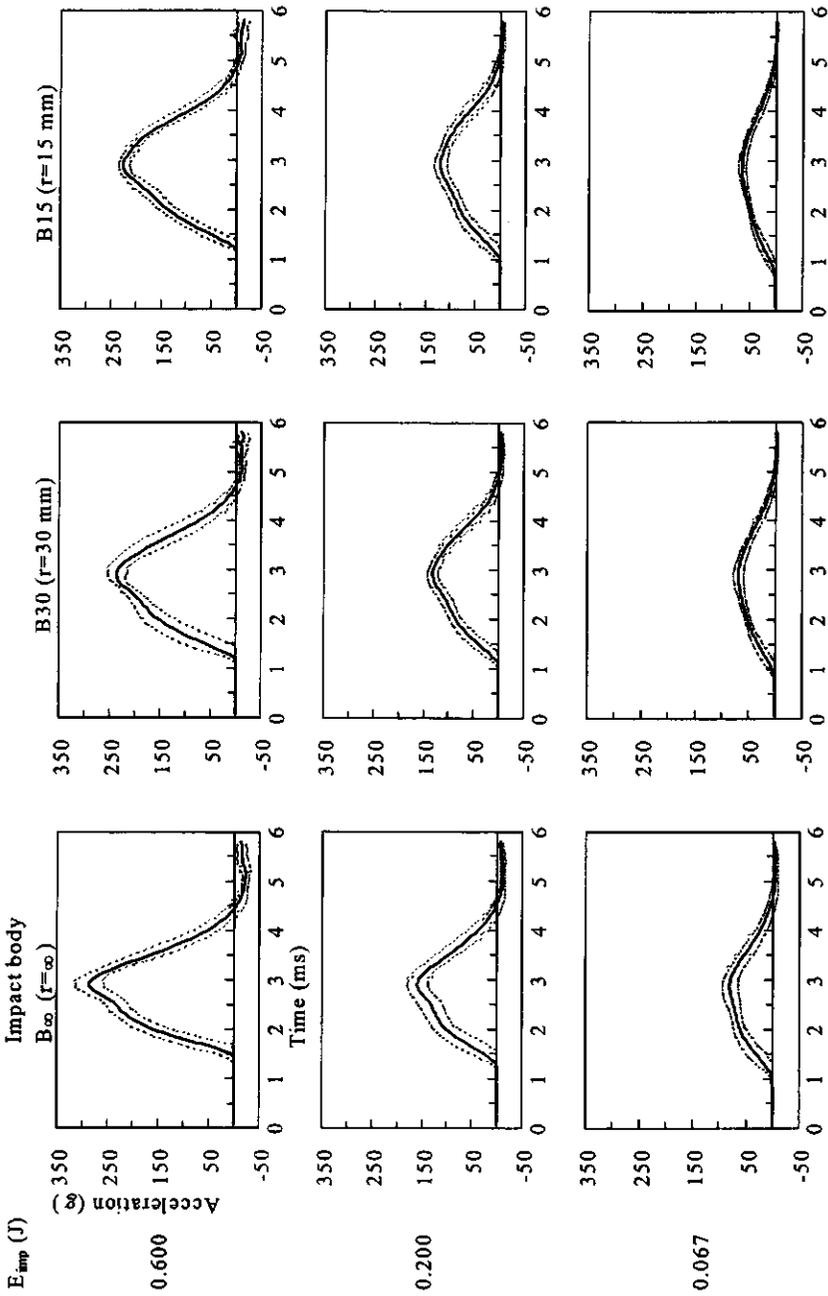


Figure 6.2. Impact characteristics of K_H tubers after 5 months storage given for nine impact treatments. Acceleration (g) versus time (ms). Bold lines represent mean values ($n = 20$); dotted lines define $\bar{X} \pm 1.96 S$ confidence interval.

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 6.4).

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 x potassium level, impact energy x storage duration, impact energy x impact body shape and impact body shape x 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 6.5) than on the volume of discoloured tissue (*ca* 75 and 95% reduction on average, respectively, Table 6.3). 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

Table 6.3. Volume of discoloured tissue ($n = 45$) after three 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 three storage durations and three impact body shapes (upper part of the table) and stored for 3, 5 or 7 months (3, 5, 7M) averaged over two potassium levels and three impact body shapes (lower part).

Treatment	Volume of discoloured tissue (mm^3)		
	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 ^{nN}	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.

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Table 6.4. Volume of discoloured tissue ($n = 45$) after three impact body treatments (B ∞ , B30, B15) in tubers from plants grown at a low and high potassium level (K_L , K_H) averaged over three storage durations and three impact energy treatments (upper part of the table) and stored for 3, 5 or 7 months (3, 5, 7M) averaged over three impact energy treatments and two 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 ^{mM}
5M	212 ^{mN}	365 ^{mM}	353 ^{mM}
7M	111 ^{oO}	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.

small difference in depth of discoloured tissue after treatment with B30 or B15.

As observed before (Table 6.5) the depth of discoloured tissue doubled when tubers were impacted with the spherical impact bodies, relative to the non-spherical impact body (Table 6.6). There was no significant difference in the effect on the depth of discoloured tissue between the two spherical impact bodies. As observed before (Table 6.4) 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 6.5. Depth of discoloured tissue ($n = 45$) after three 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 three storage durations and three impact body shapes (upper part of the table), stored for 3, 5 or 7 months (3, 5, 7M) averaged over two potassium levels and three impact body shapes (middle part) and with three impact body shapes (B_{∞} , B30, B15) averaged over two potassium levels and three 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.

Table 6.6. Depth of discoloured tissue ($n = 45$) after three impact body treatments (B_{∞} , B30, B15) in tubers from plants grown at a low and high potassium level (K_L , K_H) averaged over three storage durations and three 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 mm³, 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 6.1). 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 6.1) and dry matter content is positively related to susceptibility to tissue discolouration (Burton, 1969; Hughes, 1974, 1980a, see also Table 6.1). Van Es (1975) reported a negative relation between tuber potassium content and blackspot susceptibility.

Impact characteristics

The impact characteristics (Figure 6.2) 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 imprint of the flat impact body was less than that of the spherical ones. The quick deceleration of the flat impact body resulted 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 6.4, 6.5 and 6.6) were 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 6.5) and an average reduction of the volume of discoloured tissue of *ca* 95% (Table 6.3). 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 yielded tissue

discolouration (bruising). In our experiment, however, a different cultivar was used and the way of tuber preparation also differed from 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 for 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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CHAPTER 7

General discussion and conclusions

Outline of research programme

The research aimed to study the effect of mechanical impact on subcutaneous tissue discolouration. The first part described in this thesis consisted of an inventory of the occurrence of subcutaneous tissue discolouration and its quantification in pre-defined chain links, from field up to package. The produce-friendliness of the chain-machinery was technically analyzed (Chapter 2). Aspects like drop height, use of cushioning materials, transport speed, *etc.* were assessed. Also aspects like tuber temperature and ambient temperature during handling were taken into account. Subsequently forces present during handling were assessed and analyzed using an instrumented sphere, which recorded impact-related parameters such as acceleration, velocity and impact duration (Chapter 3).

A new pendulum-device was developed to test the effects of impact intensity and impact frequency in the laboratory (Chapter 4).

In the last part of the thesis, the effect of repetitive impacts (Chapter 5), and the effect of the impact body shape on volume and depth of subcutaneous tissue discolouration were described (Chapter 6). By applying highly standardized materials and methods, the results from the various approaches could be linked and used to further insight into the effects of mechanical force on subcutaneous tissue discolouration.

Damage classification

An important aspect of potato damage studies is damage classification. Damage in potato can be divided into different categories. Mohsenin (1986) introduced a qualitative damage classification system for fruits and vegetables (Table 7.1). Within the different types of damage, however, a detailed quantification is necessary. International agreement on a standard quantitative damage classification system based on unequivocal objective criteria and techniques of assessment would be of great help to stimulate research and interpret its results. The usefulness and applicability in practice of such a system will depend on its complexity and user-friendliness. Bouman (1995) suggested a uniform standard damage classification for potato tubers using the results of an inquiry. He also suggested to develop a standard sampling method as the basis for good damage assessment.

The research presented here focused on subcutaneous tissue discolouration. Subcutaneous tissue discolouration is a very important type of damage in Dutch

Table 7.1. Terms and definitions related to mechanical damage in fruits and vegetables (mainly after Mohsenin, 1986).

Term	Definition
Abrasion	Abrasive injury may vary in severity from separation of the periderm or skin to removal of part or the entire pericyclic cortex. Skin abrasions are difficult to detect at time of harvest, but can readily be observed after storage for a week or more at low humidities.
Bruising	Damage to plant tissue by external forces causing physical change in texture and/or eventual chemical alteration of colour, flavour, and texture. Bruising does not break the skin.
Crack	A cleavage without complete separation of the parts.
Cut	Penetration or division by the sharp edge of an object.
Distortion	A change in shape of an intact fruit or vegetable which is not characteristic for the variety.
Pressure spots	Damage to plant tissue due to pile height (static load) during storage leading to flattened and indented tissue. Physical change in texture and eventually alteration of colour, flavour and texture may occur.
Puncture	A small hole or wound on the surface made by a pointed object.
Shatter cracks	One or more tortuous cracks radiating from a point of impact.
Skin break	Fracture of the periderm or a crack limited to the skin.
Skinning	The separation of periderm from the plant part by scraping, rubbing, <i>etc.</i>
Split	Division or separation into parts.

potatoes. Subcutaneous tissue discolouration was defined as: 'all blue and blue-grey deviation in tissue colour relative to the surrounding tissue'. Other deviations in colour than blue and blue-grey were not observed. In the laboratory experiments damage of the surface of the tuber did not occur. In the present research damage is thus synonymous with subcutaneous tissue discolouration. In theory, mechanical damage may also appear as deterioration of tissue or cells without visual discolouration (Vertregt, 1968). In the experiments presented here this type of damage was not observed.

A new damage assessment protocol was developed in which potato tubers were sliced with a calibrated peeler and laid onto an illuminated glass plate. Both volume and depth of discoloured tissue were calculated by measuring the surface of discoloured tissue in consecutive slices and by adding up the number of slices with discoloured tissue. The new method is very accurate and highly reproducible, but time consuming and laborious. Therefore, it is only suitable for small-scale research application. Moreover, it is in part subjective, because discolouration is assessed by the researcher's eye. We have solved this problem by having only one observer throughout the research. For large-scale assessment, objective automated equipment may be used, although this still needs to be developed.

Chain analysis

From an analysis of representative Dutch handling-chains a number of conclusions about common practice and its effect on subcutaneous tissue discolouration could be drawn.

Facilities. Many growers and grading/packaging companies are very well equipped with potato handling machinery. However, the utilization with respect to produce-friendliness leaves much to be desired. Important shortcomings are, for example (Chapter 2),

- too high speed of transport;
- bad tuning of speeds of consecutive transporting parts (conveyers, inspection tables, etc.);
- unnecessarily high drop height;
- insufficient cushioning materials;
- inadequate bin-filling; and
- insufficient use of the conveyers capacity.

In terms of construction and technique it became clear that often major improvement could be reached with relatively small modifications. An example is the use of supporting rolls at sites where potato tubers fall. Mostly the supporting rolls of the conveyers could be displaced in order to create softer drops.

Temperature. The research showed from which links in the handling-chain subcutaneous tissue discolouration originates and to which extent (Chapter 2). More than 60% of the total damage occurred at the farm. Major variation in the level of subcutaneous tissue discolouration occurred in tubers supplied by the various growers via the corresponding grading/packaging centres. This variation could largely be accounted for by differences in tuber temperature, and differences between tuber temperature and ambient temperature during handling. Tuber temperature frequently was too low as a consequence of insufficient warming-up. Sometimes tubers were warmed up well, but cooled during truck loading at the farm due to lower temperatures in or outside the barn. Susceptibility to tissue discolouration increases at lower temperatures (e.g. Ophijs et al., 1958). Sitkei (1986) reported a decreasing elasticity of potatoes with a decreasing temperature (range 0-30 °C).

Subcutaneous tissue discolouration due to storage. Bulk storage caused a significant part of the total subcutaneous tissue discolouration, partly consisting of pressure spots (see Table 7.1), occurred (Chapter 2). As a consequence of the wet circumstances in the experimental year, ventilation rates were probably higher than normal, resulting in extra moisture losses with consequently a higher chance of the occurrence of pressure spots.

An alternative for bulk storage of potatoes could be box storage. Box storage limits pile height drastically and offers a lot of other advantages over the commonly used bulk storage. These advantages include the fact that only potato tubers that have to be delivered need to be warmed up and that poor or disease infected lots can easily be discarded.

In a recent study Molema & Scheer (1998) found that box storage resulted in substantially less weight loss than bulk storage. It was also found that the number and especially the depth of subcutaneous tissue discolouration (due to pressure spots) were substantially lower in box storage. According to the common Dutch assessment protocols potato tuber quality was much higher after box storage. However, box storage of potatoes still raises many questions that require additional research.

Underestimation of damage. A diminishing amount of discoloured tissue was observed towards the end of the chain. Damaged and already discoloured tubers may respond less to impact at every subsequent step in handling resulting in an underestimation of the 'absolute' damage in the links towards the end of the chain. A good experimental alternative could be using potatoes, free of damage and with the same susceptibility to subcutaneous tissue discolouration, at the start of every link. In the current approach this was not practicable.

Effect of growing season. The research is based on potatoes from one growing season. To compensate for this limitation, the number of grading/packaging centres and the number of growers were relatively high. To minimize variation between lots taken from the same link, sample size was larger than common in similar research. Expressing damage per link as percentage of the total damage could characterize damage probability and possibly circumvent a seasonal effect.

Damage assessment methods. In the survey work, tissue discolouration was assessed after peeling the tubers and only the surface of discoloured tissue was taken into account (Chapter 2). In the experimental research (Chapters 5 & 6) potato tubers were sliced with a calibrated peeler to quantify surface and depth of discoloured tissue, so that volume and depth of discoloured tissue could be calculated. Assessment of damage in the chain analysis (Chapter 2) differed also somewhat from that in the experiments. In the latter, tuber slices were positioned on an illuminated glass plate through which the boundary between damaged and undamaged tissue was better visible resulting in more accurate assessments than by superficial illumination. The results obtained with the two methods to quantify subcutaneous tissue discolouration may not be entirely comparable. The relationships between the results of the various methods have not been established.

Subcutaneous tissue discolouration and potato quality. The marketability of ware-potatoes may further be threatened by the ongoing upscaling of the chains, which will

presumably cause more damage and thus lower the produce quality. This trend can only be stopped if mechanical damage receives the attention in research and practice it deserves.

Impact measurements

Instrumented sphere. To improve the understanding of mechanical forces which potato tubers undergo in the chain, an accelerometer mounted to an instrumented sphere (IS) was used. This yielded insight into the 'forces' acting in the chain (Chapter 3). Number and intensity of the impacts were recorded. Since impact data, recorded by the IS, cannot be translated exactly into the damage expected, IS data were mainly used for a comparison of the load stresses between the chain links. Restriction of the used IS is that static load, which is also a cause of subcutaneous tissue discolouration, and occurs e.g. during bin or bunker storage, cannot be measured. Also 'mangle effects', e.g. at defective roller graders, cannot be quantified with the IS.

Moreover, some physical properties of the sphere, such as shape, weight and elasticity, are not corresponding to those of potato tubers. Especially the sphere's relatively low elasticity increased the chance of bouncing. Bouncing, IS-tuber contacts and IS-machine contacts explain why the number of recorded impacts in the whole chain (ca 340) is higher than the 72 drops determined in the chain analysis. Nevertheless, the number of impacts potato tubers are exposed to is still too high. The major advantage of the IS is its ability to measure objectively and reproducibly.

In addition to the IS used in this research there is also a sphere available that quantifies static and dynamic load. At the start of the current research programme, a lot of expertise was available on the sphere used (IS100), therefore this IS was selected.

Reference measurements. To relate recorded impact data to impact data of well-defined drops, reference measurements were carried out under controlled conditions with a drop tester developed for this purpose (Chapter 3). When using other instruments than the IS used here, to characterize impacts, the drop tester can be used for calibration of these instruments. The drop tester can also be used to quantify the effect of precisely-known impacts on potato damage.

Impact effects

A new pendulum. The technical analysis of the chain (Chapter 2) and the IS measurements (Chapter 3) carried out in parallel, resulted in useful information concerning type and frequency of the acting forces. To quantify effects of impact force and impact frequency it was required to simulate impacts at laboratory scale under

controlled conditions. For this purpose different techniques and instruments were available, but none of these met the demands set by the research objectives. Therefore a new instrument was developed according to the principle of a pendulum (Chapter 4). This computer-controlled pendulum offered the possibility to impact potato tubers with a pre-determined amount of impact energy. Impact body shape, impact body weight and drop height could be varied. So different shapes of machine parts, with which potatoes are colliding in practice, could be simulated. Impact data were stored and subsequent calculations and analyses could be easily made. Reproducibility of the pendulum method turned out to be high. Disadvantage of the instrument is that potato tubers need to be cut to fix the pieces to the sample holding system according to the principle reported by Noble (1985). Noble stated that his technique does not influence results. The pendulum has a wide range of potential applications and is especially suitable to study dose-effect relations, particularly in visco-elastic produce.

Site specific impact probability. The pendulum was used to study the effect of repetitive impacts at the same tuber site (Chapter 5). This research was initiated because most of the potatoes are more or less elliptically shaped with an eccentric centre of gravity. During handling certain tuber sites have a higher probability to be hit. It would be of great interest to calculate these probabilities for some well-defined tuber shapes of commonly used cultivars.

Damage threshold. All impacts administered in the laboratory experiments yielded subcutaneous tissue discolouration. Also in the experiment with the lowest energy level (0.067 J), the damage threshold was exceeded. Despite the fact that the damage threshold is affected by many factors, it would be useful to determine damage thresholds for different cultivars under controlled conditions, so that estimates of damage thresholds can be made for other conditions by extrapolation.

Repetitive impacts. Splitting the impact energy over a number of equal impacts resulted in less damage than when all impact energy was applied in one impact. Thus, when a potato has to overcome a specific drop height this can best be done in different steps. Furthermore it became clear that when potatoes are damaged at a certain tuber site it might be important, depending on the use of the potato, to avoid another impact at the same tuber site.

The results showed that both volume and depth of damaged tissue proportionally increased with the number of impacts (up to 8; Chapter 5). It is an illusion to suppose that already damaged potatoes can be handled roughly.

It is commonly believed that low-energetic impacts do not or hardly give damage. Van Loon & Meijers (1980) and De Haan (1987) therefore suggested to limit drop heights to 30-40 cm. In current handling little attention is paid to this type of impact. However, the effect of a certain dose as one impact or divided over a number of equal impacts resulted in different amounts of damage (Chapter 5). The results of this study

showed that although splitting the impact energy reduces subcutaneous tissue discolouration, tissue still showed discolouration.

Sitkei (1986) stated that loads, individually smaller than those corresponding to the biological yield point, could damage potato tissue when repeated many times. So low-energetic impacts can also play an important role in the occurrence of subcutaneous tissue discolouration.

Nevertheless the depth of damage is crucial because the depth of tissue discolouration has a major effect on the amount of produce lost during processing and preparation especially when potato peeling is automated.

Sequential impacts. No difference between the effect of an increasing or decreasing order of impact energy could be established in the experiments described in Chapter 5. When potatoes have to overcome a number of drop heights with impact energies comparable to those used in the experiments it appears of no use to arrange them in a specific order.

Interval between impacts. In this research, the time between consecutive impacts was *ca* 10 s. In practice this interval may vary from less than 1 second to various months. Recuperation of tuber tissue may occur and may depend on impact interval. Since the ability to recuperate is not known, additional research may help to create a better understanding of this phenomenon.

Impact interactions. Possible interactions between the effects of impacts at different sites of the tuber are not known and would be of great interest to be studied.

Impact body shape. The use of spherical shapes at sites where potatoes may be impacted has to be considered with great care. Some examples of spherical shapes are rods on machines for harvest and grading, and supporting rolls. For the shapes studied, the spherical ones doubled the depth and volume of subcutaneous tissue discolouration relative to the flat one (Chapter 6). Brook (1996) reported that a small radius of curvature concentrates the impact forces on a small area resulting in higher tissue stress and more tissue discolouration. The effect of lower impact energy levels was larger for spherical impact bodies than for non-spherical impact bodies. So, when spherical impact bodies are present even the low-energetic impacts may be important.

Within the spherical shapes used (radius of curvature 15 and 30 mm), the radius of curvature of the impact body did not affect the amount of subcutaneous tissue discolouration. Tuber curvature at the impact site, however, affected depth and volume of subcutaneous tissue discolouration.

Tuber variation

Experimental design. One of the main problems in studying susceptibility to subcutaneous tissue discolouration is the large variation in the observed amount of tissue discolouration after identical treatments (Chapters 2, 5 & 6) of potato tubers of the same cultivar, grade and origin. This even holds for tubers from the same plant or stem. An explanation for this phenomenon is variation in dry matter content (Veerman *et al.*, 1996).

It became clear that for scientific research on the subject of relations between impact and subcutaneous tissue discolouration preliminarily investigations by means of literature and experiments are necessary to design most suitable experimental set-up, including the number of repetitions and the sampling rate to obtain representative results. Operational considerations may play a role so that compromises are often inevitable.

Control of growth and storage. In research as with the pendulum it is vital to use potatoes in which during growth and the subsequent storage period, as much variables as possible, are conditioned and controlled (Chapters 5 & 6). For the experiments potatoes were grown on a soil of which variables such as nutrients and organic matter content were quantified beforehand. This information could be taken into account at the initiation of the experimental set-up so that variation in results could be minimized. Tubers were harvested manually, free of damage, and stored individually on soft ventilating pads. During the period of storage a highly accurate regime of temperature and relative humidity was maintained to keep potatoes in an optimal condition.

Other approaches

Parallel to the research presented, other research options exist to decrease, control or prevent subcutaneous tissue discolouration by mechanical impact. Main goal in these approaches is to prevent some specific biochemical reactions responsible for the phenomenon of tissue discolouration (Stevens & Davelaar, 1996; Stevens & Davelaar, 1997; Stevens *et al.*, 1998).

However, for further utilization of potato tubers, impact-induced deviation in tissue texture and wound respiration (Pisarczyk, 1982) may remain undesirable. Therefore on the short-term and as long as there is a lack of alternatives, limitation of mechanical impact remains crucial to avoid mechanical damage.

Prospects

Utilization of facilities. The results offer leads to improve the use of technical supplies.

Aspects such as well-tuned transporting speeds, effective use of cushioning materials, as well as reducing the number and intensity of drops can frequently be realized in a simple, fast and relatively cheap way. Using only handling units, which suit specific aims, can lower the number of impacts. Bin-filling can take place layer by layer (terrace building) so that many impacts can be avoided. A prerequisite for improvement is that potato tubers are sufficiently warmed up after cold storage. By warming up potatoes sufficiently and in time, and by creating conditions which will avoid a rapid change in temperature, the potential for subcutaneous tissue discolouration can be reduced substantially.

Logistics. Commonly potato tubers have to pass standard routes, which often lack flexibility, to reach their final destination. In many cases transporting units and bunkers link the main operations such as truck unloading, grading, washing and packaging. The results show that interim storage causes subcutaneous tissue discolouration. This effect is an accumulation of effects of both the bunker and the extra transporting units required. Bunkers fulfil a buffering function and are of great importance in handling chains, but that they are part of the route is frequently not required. When routing is planned optimally, one or more interim storages can be avoided. In this way the number of handling operations can be reduced substantially. Therefore a highly flexible logistical concept is required.

Spherical tubers. The negative effect of small radii of tuber curvature at the tangent plane and the probability of repetitive impacts at the same site advocate spherical potatoes with a concentric point of gravity so that the impact probability is equal at each tuber site. In this case the number of tuber sites with a small radius of curvature at the tuber surface is *nil*. Disadvantage of more spherical tuber shapes is the higher probability of rolling, increasing the number and intensity of impacts. On balance, more spherically-shaped tubers probably result in a more uniform damage distribution all over the tuber and a relatively larger tuber surface will be damaged. However, the depth of tissue discolouration may decrease.

Modelling of discolouration probability. With the results obtained, the basis for the prediction of tissue discolouration and for simulation and design of optimal handling-chains is laid. However, it is highly complex to predict effects of interactions between different types of impacts at the same tuber site. Therefore it is important, not only to simulate single handling operations, but also to integrate a series of handling operations representative for practice. Probably, predictability will be more complex due to the interaction of the tuber shape with the effect of mechanical force. For each tuber shape the behaviour of individual tubers travelling over a long distance in a produce stream (> 300 m) has to be studied by modelling or experimentation.

Also it is of great interest to predict the allowed exposure to impact for a certain acceptable level of damage. Therefore it is useful to create data bases so that by neural

networks *e.g.* as described by Sascha *et al.* (1999) information can be integrated to develop a highly intelligent system able to predict effects of handling for well-defined produce.

Research protocols. Both for the survey work (Chapters 2 & 3) and for the experimental research (Chapters 5 & 6) protocols were developed which can be widely used in similar research in production chains of seed-, processing-, fastfood- and starch potatoes. With these protocols tissue discolouration in handling-chains can be determined, handling-chains can be assessed for produce-friendliness (instrumented sphere) and impacts can be simulated in detail to study dose-effect relations. The protocols are also suitable for comparable research in other production chains like those of flower bulbs, fruits, eggs, *etc.*.

Economic perspectives. Implementation of the knowledge obtained in this study can lead to a substantial decrease of damage and thus to less qualitative and quantitative losses. Consequently the financial losses can also be reduced. To improve practice all partners participating in the chain should benefit financially from reduced damage.

Scientific progress. The study yielded more insight into the effect of mechanical impact on subcutaneous tissue discolouration. Assessment of utilization and produce-friendliness indicated weak links in the handling-chain, which can be directly improved. Damage accumulation in the chain was quantified and related to the forces acting in the chain. Pendulum experiments elucidated effects of both repetitive impacts and impact body shape on subcutaneous tissue discolouration.

Conclusions

The research yielded new information about major effects and their interactions. The problem inventory made clear from which links in the handling-chain subcutaneous tissue discolouration originates and at what degree. Using the instrumented sphere (IS100) a better understanding was obtained with respect to the 'forces' acting in the chain.

Concrete results on dose-effect relations were obtained. In particular the effect of repetitive impacts on potatoes and the effect of shape (curvature) of both potato and impact body became clear. Consequently some commonly used insights have to be reconsidered. For example the effect of low-energetic repetitive impacts on subcutaneous tissue discolouration cannot be neglected. Although there are still questions left, the obtained insight offers the potato sector perspectives to make adequate changes in technique and technology. These changes regard both the number of impacts and the intensity of impacts and should result in a produce which can be offered to the consumer in a condition (almost) free of subcutaneous tissue discolouration. Moreover, when utilization of machinery is optimized damage

reduction can be substantial. To optimize the whole potato handling-chain with respect to produce-friendliness additional research is necessary. Additional research should focus on fundamental relations that are currently missing and on developing an optimal logistic handling concept. Crucial in this concept are flexibility and produce-friendliness. Ideally, potatoes may be transported along different routes and the number and intensity of impacts are minimal. Also repetitive impacts on the same tuber site and the use of spherical impact bodies are avoided. The effect of time intervals between consecutive impacts has to be studied. Tuber tissue may be able to recover more or less from damage when time between impacts is long enough. Further it was not clear at which curvature spherical impact bodies start to affect damage significantly.

To create a more produce-friendly attitude of growers and other participants in the potato handling-chain a more clear differentiation between 'good and poor quality potatoes' is necessary. A financial incentive could have a substantial effect, probably resulting into potatoes with a high quality, *i.e.* free of subcutaneous tissue discolouration.

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Summary

Potato is an important food crop in many countries all over the world. It produces tubers below-ground, which are harvested by complicated machine operations and may need to be stored for several months. From harvesting onwards these vegetative storage organs experience mechanical stress, which may reduce the quality of the produce. A major quality problem in potato is subcutaneous tissue discolouration: this defect can be defined as all blue and blue-grey deviation in tissue colour relative to the surrounding tissue. Subcutaneous tissue discolouration significantly lowers the market value of potatoes.

Over the last decades developments in potato production and mechanization were rapid, aiming to increase capacity and to reduce costs. Concomitantly, potatoes can be damaged more easily. Despite considerable research on subcutaneous tissue discolouration, the problem is still far from being solved: there is still a need for further research so that potatoes can be offered to the consumer in a (almost) perfect condition. To reach this goal further insight into the relation between mechanical force and subsequent subcutaneous tissue discolouration is essential. This thesis deals with this relation. The study was limited to ware-potatoes (*cv.* Bintje, grade 50-60 mm) for the fresh market.

Analysis of Dutch ware-potato handling-chains

Representative Dutch ware-potato handling-chains were analyzed to assess where in the handling-chain subcutaneous tissue discolouration originates and to what extent each link in the chain contributes to the total amount of subcutaneous tissue discolouration. Besides, the characteristics of the handling-chains in terms of number, type and height of drops, distance, direction and speed of transportation and change in speed of transportation were assessed. The handling-chain was divided into four phases, each consisting of one or more links. The *harvest* phase comprised lifting through bin-filling at the farm, the *storage* phase storage at the farm, the *transport* phase shovelling through truck loading at the farm and the *packaging* phase truck unloading through packaging at the grading/packaging centres. On average, individual tubers travelled 346 m on their way through the handling-chain: 43 m during harvest, 39 m during transport and 264 m during packaging. The handling-chain comprised on average 72 drops with heights exceeding 10 cm, 49 (68%) of them even exceeding 30 cm. Cushioning material was involved in *ca* 50% of the drops. The number and height of drops were too high and the use of cushioning material was insufficient to keep subcutaneous tissue discolouration at an acceptable, low level. On average, *ca* 50% of the registered drops involved a change in direction which may result in extra impact between tubers and the material they fell on. The speeds of conveying belts were often too high and not in balance with each other or with other transporting parts like roller

tables for tuber inspection. Of the measured transport speeds, 46% exceeded 0.6 and 8% exceeded 0.9 m s⁻¹. The contribution to the total amount of subcutaneous tissue discolouration was 16% for harvest, 22% for storage, 27% for transport and 35% for packaging. Because of pile height and imperfect ventilation, which leads to moisture loss, the majority of subcutaneous tissue discolouration caused by storage appeared as pressure spots. Due to accumulation of subcutaneous tissue discolouration, the absolute increase may be underestimated towards the end of the chain because as the amount of discoloured tissue increases it will be more difficult to discern 'new' tissue damage. From storage through packaging 80% of the variation in subcutaneous tissue discolouration was accounted for by the variation in the temperature of the tuber and the ambient temperature at removal from the shed and by the differences in the produce-friendliness of the different combinations of grading and packaging. The tuber temperature, which was often too low, was the most influential of these factors.

Parallel to the chain analysis impacts were measured with an instrumented sphere (IS). The IS characterizes impacts in terms of peak-acceleration and velocity-change. The major advantage of the IS is its ability to measure objectively and reproducibly. A straightforward relationship between acceleration and velocity-change for different drop heights on the materials tested was established by means of a specially-designed drop simulator. In the entire chain the IS recorded on average *ca* 340 impacts exceeding 30 g. The number of impacts was 38 during harvest, 35 during transport and 266 during packaging. On average 98% of the impacts did not exceed 150 g and 58% of the impacts was in the class 30-50 g. The difference between the number of recorded impacts (*ca* 340) and drops determined in the chain analysis (*ca* 72) can be explained by IS-tuber contacts, by IS-machine contacts (*e.g.* during grading and washing) and by the physical properties ('bouncing') of the IS. Due to the physical properties of the IS the number of impacts measured with the IS was probably overestimated, relative to that experienced by potatoes. One should be conscious, however, that the IS data may be biased by differences in properties between the IS and a potato. By using the instrumented sphere a better understanding was obtained with respect to the 'forces' which potatoes undergo in the handling-chain.

Pendulum

Tubers may be impacted several times at the same site by impact bodies of different shapes as a consequence of the large number of impacts and the eccentric centre of gravity in a tuber. Effects of repetitive impacts at the same site of the tuber and of impact body shape can be studied with a pendulum. For those purposes the pendulum needs to be very accurate and therefore a new pendulum was designed. Its applicability and accuracy were tested. The construction of the sample holding system enabled a very precise positioning of potatoes. Halved potatoes, that were initially free of tissue discolouration, were used. The halves had a thickness of *ca* 30 mm. The volume and depth of the discoloured tissue that arose after impacting precisely with the pendulum

were calculated by measuring the surface of discoloured tissue in consecutive slices on an illuminated glass plate and by adding up the different slices with discoloured tissue. The versatility of the impact body allowed the use of different shapes, masses and materials. For operating and controlling the pendulum a computer program was developed. The computer calculated the real potential impact energy, the energy absorbed, velocity just before impact, duration of impact, maximum deceleration of the impact body, duration from starting the impact till the time of maximum deceleration and the velocity just after impact. The realized potential impact energy, the realized impact velocity and the realized impact energy deviated on average *ca* 0.5, 1.5 and 3.5%, respectively, from the set values. The pendulum-device proved to be an adequate tool to impact tubers precisely and reproducibly at a desired rate and to obtain detailed information about pre-impact, impact and post-impact events.

Impact dose

The tubers were from plants grown at two different levels of potassium (*i.e.* susceptibility to tissue discolouration) and stored for 3, 5 or 7 months.

In laboratory experiments the effect of repetitive impacts on subcutaneous tissue discolouration was studied. The relation between one or more doses of impact energy delivered by the pendulum at the same tuber site and the resulting volume and depth of discoloured tissue was investigated. The experiments were done with a spherical impact body with a radius of curvature of 30 mm and a diameter of 30 mm. The tuber pieces were impacted on a site perpendicular to the middle of the distance between rose and heel end. An impact energy of 0.6 J, corresponding to a drop of an average tuber of *ca* 50 cm, was taken as a standard and included in all experiments. The time between consecutive impacts was *ca* 10 s. When splitting 0.6 J over 9 equal impacts there was an average reduction of depth and volume of tissue discolouration of 33 and 64%, respectively, relative to one impact of 0.6 J only. There was an average reduction of the depth and volume of damaged tissue of *ca* 80 and *ca* 95%, respectively, by reducing the impact energy from 0.6 to 0.067 J. The volume and depth of discoloured tissue increased with the number (1-8) of 0.3 J impacts.

Although splitting the impact energy reduces subcutaneous tissue discolouration, tissue still showed discolouration after a series of low-energetic impacts.

Impact body shape

The relation between the radius of curvature of the impact body at a given level of energy and the subsequent discolouration of tissue was studied with potatoes similar to those used in studying the effect of repetitive impacts. In practice, the radius of curvature of potato tubers as well as of other impact bodies varies. The shape of the impacting surface appeared to be of major importance in the process that causes subcutaneous tissue discolouration. In the experiments a non-spherical (radius of

curvature ∞) and two spherical (radius of curvature 15 and 30 mm) impact bodies were used. The non-spherical impact body gave higher peak-accelerations as a result of the larger contact area during impact, relative to the spherical ones. The spherical impact bodies, relative to the non-spherical impact body, doubled the volume and depth of discoloured tissue.

Potassium fertilization and storage duration

Potatoes grown at a low potassium level were more damaged by impact than potatoes grown at a high potassium level. The former had a higher dry matter content which is positively related to susceptibility to tissue discoloration.

In contrast to the generally accepted assumption that tissue discoloration increases with an increase in storage duration, we also observed the opposite. The observation was made in some experiments that tissue discoloration decreased with a prolonged storage duration and that this decrease was associated with the onset of sprouting and the attendant additional water loss. Storage conditions in our experiments differed from those in practice.

Implications

During the chain analysis it was noticed that many growers and grading/packaging companies were very well equipped with machinery, the utilization of which, unfortunately, left in many cases much to be desired. It was observed that more than 60% of the total subcutaneous tissue discoloration was caused at the farm. As an alternative for bulk storage of potatoes, box storage is suggested.

To explain consequences of current handling-chains, comparison to well-defined reference measurements is needed. The importance of a standard, objective system to classify damage is corroborated by this study. For a reproducible simulation of impacts under controlled conditions, it is advantageous to use a computer-controlled pendulum. The pendulum experiments on dose-effect relations yielded concrete results, that urge a revision of some commonly-used principles of potato handling such as the supposed harmlessness of low-energetic repetitive impacts.

To optimize the produce-friendliness of the potato handling-chain additional research is necessary, aimed at the pursuit of missing knowledge of dose-response relations and the development of an improved concept of logistics. Crucial for the implementation of this new knowledge is that all partners participating in the chain benefit financially.

Improvement of the chain

The results of this thesis facilitate some beneficial changes in technique and technology within the potato sector. To supply potatoes to the users free of damage,

the design of the whole handling-chain should be revised, based on current and new knowledge. In the meantime significant improvements of specific links may be attained. A few examples:

- Optimal utilization of machinery can reduce subcutaneous tissue discolouration substantially;
- In current handling-chains a more efficient planning can reduce the use of bunkers and the subsequent occurrence of subcutaneous tissue discolouration caused by static load and transport to and from the bunkers;
- Development of more flexible logistic concepts stimulates the use of the shortest (less harmful) handling route;
- A great deal of subcutaneous tissue discolouration can be prevented by an adequate temperature control of the tubers;
- In future, potato handling the number and energy of impacts should be lowered and the use of spherical impact bodies should be avoided as much as possible;
- Instrumented sphere measurements are useful to get insight into the forces acting in the chain and for a comparison of the load stresses in the various chain links.

The approach adopted in this study and the assessment protocols developed, can also be of use for similar research in other potato production chains and production chains like those of flower bulbs, fruits, *etc.*. The obtained knowledge can further be of use in developing equipment, in upgrading present lines and in setting up new, more produce-friendly handling lines and concepts.

Samenvatting

In veel landen in de wereld speelt het gewas aardappel een belangrijke rol in de voedselvoorziening. Het gewas produceert ondergrondse knollen, die worden geoogst middels gecompliceerde machinale handelingen en meestal vele maanden worden bewaard. De vegetatieve opslagorganen ondervinden in de bewerkingsketen, beginnend bij de oogst, mechanische stress die kan leiden tot kwaliteitsvermindering van het product. Een belangrijk probleem bij aardappelen is onderhuidse weefselverkleuring: deze tekortkoming kan worden gedefinieerd als alle blauwe en blauwgrijze afwijkingen in weefselkleur ten opzichte van het omliggende weefsel. Onderhuidse weefselverkleuring is een gevolg van mechanische stress en verlaagt de marktwaarde van aardappelen aanzienlijk.

De laatste decennia waren er veel ontwikkelingen ten aanzien van zowel de productie als de mechanisatie van de teelt en bewerking van aardappelen. Doel hiervan was het verhogen van de productiviteit en het verlagen van de kosten. Aardappelen kunnen door deze recente ontwikkelingen gemakkelijker beschadigen. Ondanks veel onderzoek naar onderhuidse weefselbeschadiging is het probleem nog niet opgelost. Verder onderzoek is nog steeds noodzakelijk om aardappelen in een (vrijwel) perfecte conditie aan de consument te presenteren. Om dit doel te bereiken is meer inzicht nodig in de relatie tussen mechanische belasting en de hiermee gepaard gaande onderhuidse weefselbeschadiging. Dit proefschrift handelt over deze relatie. Het onderzoek beperkte zich tot consumptieaardappelen (cv. Bintje, sortering 50-60 mm) bestemd voor de versmarkt.

Analyse van Nederlandse bewerkingsketens voor consumptieaardappelen

Representatieve Nederlandse bewerkingsketens van consumptieaardappel werden geanalyseerd om te beoordelen waar en in welke mate onderhuidse weefselbeschadiging ontstaat. Daarnaast werden verschillende kenmerken van de bewerkingsketen in termen als aantal, type en hoogte van vallen, af te leggen afstand, richting en snelheid van transport en veranderingen in transportsnelheid beoordeeld. De bewerkingsketen werd hiertoe onderverdeeld in vier fasen, ieder bestaand uit één of meer schakels. De *oogstfase* omvatte het rooien tot en met de opslag van aardappelen op de boerderij, de *bewaarfase* de opslag op de boerderij, de *transportfase* het opscheppen tot en met het laden van de vrachtwagen op de boerderij en de *verpakkingsfase* het lossen van de vrachtwagen tot met het verpakken op het sorteer/verpakkingsbedrijf. Individuele knollen legden gemiddeld een afstand van 346 m af op hun weg door de bewerkingsketen: 43 m in de oogstfase, 39 m in de transportfase en 264 m in de verpakkingsfase. De bewerkingsketen omvatte gemiddeld 72 vallen met hoogtes groter dan 10 cm, waarvan 49 (68%) zelfs groter dan 30 cm. Circa 50% van de vallen vond plaats op plekken waar gebruik gemaakt was van bekledingsmateriaal. Het aantal en de hoogte van de vallen waren te groot en het

gebruik van bekledingsmateriaal was onvoldoende om onderhuidse weefselverkleuring op een acceptabel (laag) niveau te houden. Van het aantal geregistreerde vallen ging gemiddeld *ca* 50% gepaard met een verandering van richting, die extra mechanische belasting van knollen tot gevolg kan hebben. Snelheden van transportbanden waren vaak te hoog en niet goed afgestemd op elkaar of op andere transporterende eenheden zoals roltafels voor knolinspectie. Van de gemeten transportsnelheden overschreed 46% 0,6 en 8% 0,9 m s⁻¹. De bijdrage aan de totale hoeveelheid onderhuidse weefselbeschadiging was 16% voor de oogstfase, 22% voor de bewaarfase, 27% voor de transportfase en 35% voor de verpakkingsfase. Door de combinatie van te hoge stapeling (storthoogte) en ineffektieve ventilatie, resulterend in vochtverlies, manifesteerde een belangrijk deel van de onderhuidse weefselverkleuring veroorzaakt tijdens de bewaring zich in de vorm van drukplekken. Als gevolg van accumulatie van onderhuidse weefselbeschadiging kan de absolute toename bij het voortschrijden in de keten zijn onderschat omdat bij toenemende beschadiging het steeds lastiger wordt om 'nieuwe' beschadiging vast te stellen. In het traject van bewaring tot en met de verpakking kon 80% van de variatie in onderhuidse weefselbeschadiging worden verklaard door verschillen in knol- en omgevingstemperatuur bij het verwijderen uit de bewaarplaats en door verschillen in productvriendelijkheid tussen de sorteer/verpakkingsbedrijven. De knoltemperatuur, die vaak te laag was, had hierbij de grootste invloed.

Parallel aan de ketenanalyse zijn dynamische belastingen (botsingen) gemeten met een elektronische meetbol (Instrumented Sphere, IS). De IS karakteriseert botsingen in termen van piekversnelling en snelheidsverandering. Het voornaamste voordeel van de IS is de mogelijkheid om objectief en reproduceerbaar te meten. Een rechtstreeks verband tussen versnelling en snelheidsverandering voor de onderzochte materialen bij verschillende valhoogtes werd vastgesteld met behulp van een hiervoor speciaal ontworpen valsimulator. In de gehele keten werden door de IS gemiddeld 340 botsingen gemeten boven 30 g. Het aantal botsingen bedroeg 38 tijdens de oogstfase, 35 tijdens de transportfase en 266 tijdens de verpakkingsfase. Gemiddeld was de piekversnelling bij 98% van de botsingen lager dan of gelijk aan 150 g en 58% was in de klasse 30-50 g. Het verschil tussen het aantal gemeten botsingen (*ca* 340) en vallen bepaald in de ketenanalyse (*ca* 72) kan worden verklaard door IS-knol contacten, door IS-machine contacten (b.v. tijdens het sorteren en wassen) en door de fysische eigenschappen ('stuiteren') van de IS. Als gevolg van deze fysische eigenschappen zal het aantal botsingen waaraan aardappelen worden blootgesteld waarschijnlijk lager zijn. Ondanks dat IS data op voorhand verschillen van data gemeten aan 'echte' aardappelen, is door het gebruik van de IS een beter inzicht verkregen in de krachten die aardappelen ondergaan in de bewerkingsketen.

Pendulum

Knollen kunnen verschillende malen worden belast op dezelfde plek, door

botsingslichamen met verschillende vormen, als gevolg van het grote aantal botsingen en het excentrische zwaartepunt van de aardappel. Het effect van herhaald belasten van dezelfde plek op de knol en van de vorm van het botsingslichaam kan worden onderzocht met een pendulum. Voor deze doelen dient het pendulum erg nauwkeurig te zijn. Deze eis leidde tot het ontwikkelen van een nieuw pendulum. De toepasbaarheid en nauwkeurigheid ervan werden onderzocht. De constructie van het monsterhoudersysteem maakt een exacte positionering van aardappelen mogelijk. In de experimenten werden gehalveerde aardappelen, vrij van onderhuidse weefselbeschadiging, gebruikt. De knolhelften hadden een gemiddelde dikte van ca 30 mm. Het volume en de diepte van het verkleurde weefsel, ontstaan na het exact belasten met het pendulum, werden berekend door het meten van het verkleurde oppervlak in opeenvolgende knolschijfjes op een verlichte glasplaat en door het tellen van het aantal schijfjes per knol met een verkleuring.

De uitwisselbaarheid van het botsingslichaam bood de mogelijkheid om verschillende vormen, massa's en materialen te gebruiken. Voor het bedienen en controleren van het pendulum werd een computerprogramma ontwikkeld. De computer berekende de werkelijke potentiële botsingsenergie, de geabsorbeerde energie, de snelheid juist voor de botsing, de duur van de botsing, de maximale vertraging van het botsingslichaam, de duur van de periode tussen het begin van de botsing en het moment van maximale vertraging en de snelheid juist na de botsing. De gerealiseerde potentiële botsingsenergie, de gerealiseerde botsnelheid en de gerealiseerde botsingsenergie weken gemiddeld respectievelijk ca 0,5, 1,5 en 3,5% af van de beoogde waarden. Het pendulum bleek een adequaat instrument om knollen nauwkeurig en reproduceerbaar te belasten en om gedetailleerde informatie te verkrijgen over relevante parameters voor, tijdens en na de botsing.

Impact dosis

In pendulum experimenten werden knollen gebruikt van planten geteeld bij twee niveaus van kalium-bemesting (corresponderend met gevoeligheid voor weefselverkleuring). Beide typen knollen werden 3, 5 of 7 maanden bewaard.

In laboratoriumproeven werd het effect van herhaald belasten op onderhuidse weefselbeschadiging onderzocht. Het verband tussen één dosis of een aantal doses botsingsenergie, gegeven middels het pendulum, op dezelfde plek van de knol en het hieruit voortvloeiende volume en de diepte van het verkleurde weefsel werd onderzocht. De experimenten werden uitgevoerd met een bolvormig botsingslichaam met een kromtestraal van 30 mm en een diameter van 30 mm. De knoldelen werden belast op een plek loodrecht op het midden tussen top- en navelind. Een botsingsenergie van 0,6 J, overeenkomend met een val van een gemiddelde knol van ca 50 cm, werd als standaard gebruikt en toegepast in alle experimenten. De tijd tussen opeenvolgende botsingen was ca 10 s. Het verdelen van 0,6 J over 9 gelijke botsingen reduceerde de diepte en het volume van beschadigd weefsel met gemiddeld

respectievelijk 33 en 64%, ten opzichte van die bij één botsing van 0,6 J.

Gemiddeld was de reductie van diepte en volume van beschadiging respectievelijk ca 80 en 95% door de botsingsenergie terug te brengen van 0,6 naar 0,067 J. Volume en diepte van verkleurd weefsel namen toe met het aantal (1-8) botsingen van 0,3 J. Alhoewel het verdelen van botsingsenergie over een aantal botsingen onderhuidse weefselbeschadiging vermindert, toonde het weefsel toch nog verkleuring bij herhaalde laag-energetische botsingen.

Vorm botsingslichaam

Het verband tussen de kromming van het botsingslichaam bij een gegeven hoeveelheid energie en de hieruit voortkomende weefselverkleuring werden onderzocht met aardappelen gelijk aan die gebruikt bij het bestuderen van het effect van herhaald belasten. In de praktijk variëren zowel de kromming van aardappelknollen als die van andere botsingslichamen. De vorm van het botsingslichaam van het pendulum bleek van groot belang in het proces waardoor onderhuidse weefselbeschadiging wordt veroorzaakt. In de proeven werden een plat (kromtestraal ∞) en twee bolvormige (kromtestraal 15 en 30 mm) botsingslichamen gebruikt. Het platte botsingslichaam gaf hogere piekacceleraties, als gevolg van een groter contactoppervlak tijdens een botsing, ten opzichte van die bij de bolvormige. De bolvormige botsingslichamen verdubbelden, in vergelijking met de platte, het volume en de diepte van verkleurd weefsel.

Kalium bemesting en bewaarduur

Aardappelen geteeld met een lage K-bemesting werden meer beschadigd door botsing dan aardappelen geteeld met een hoge K-bemesting. Eerstgenoemde hadden een hoger drogestof-gehalte hetgeen de gevoeligheid voor weefselverkleuring verhoogt.

In tegenstelling tot de algemeen gangbare veronderstelling dat weefselverkleuring toeneemt met een toename van de bewaarduur, werd ook het tegenovergestelde waargenomen. In enkele proeven werd vastgesteld dat weefselverkleuring afnam met de bewaarduur; deze afname werd in verband gebracht met het aanvangen van de kieming en het hiermee gepaard gaande waterverlies. De bewaarcondities in de proeven verschilden met die in de praktijk.

Praktische betekenis

Tijdens de ketenanalyse werd geconstateerd dat veel telers en sorteer/verpakkingsbedrijven erg goed waren uitgerust met machines. Het gebruik hiervan liet jammer genoeg in veel gevallen te wensen over. Er werd vastgesteld dat meer dan 60% van de totale hoeveelheid onderhuidse weefselverkleuring werd veroorzaakt op de boerderij. Als alternatief voor bulkopslag wordt kistenopslag

genoemd.

Om gevolgen van huidige bewerkingsketens te kunnen verklaren kan gebruik worden gemaakt van goed gedefinieerde referentiemetingen. De noodzaak van een standaard, objectief systeem om beschadiging te classificeren wordt bevestigd door deze studie. Voor een reproduceerbare simulatie van botsingen onder gecontroleerde omstandigheden is het aan te bevelen om gebruik te maken van een computer-gestuurd pendulum. De pendulum experimenten over dosis-effect relaties leverden concrete resultaten die aansporen tot herziening van een aantal algemeen gangbare principes bij aardappelbewerking, zoals de veronderstelling dat laag-energetische botsingen niet schadelijk zijn.

Om de productvriendelijkheid van aardappelbewerkingslijnen te optimaliseren is aanvullend onderzoek nodig, gericht op het genereren van ontbrekende kennis over dosis-respons relaties en op de ontwikkeling van een verbeterd logistiek concept. Cruciaal voor de implementatie van deze nieuwe kennis is dat alle deelnemende partijen in de keten hier financieel voordeel bij hebben.

Verbetering van de keten

De resultaten van dit proefschrift maken het doorvoeren van een aantal verbeteringen in techniek en technologie binnen de aardappelsector mogelijk. Om de gebruikers van aardappelen te voorzien die vrij zijn van schade, zou het ontwerp van de hele bewerkingsketen moeten worden herzien, gebaseerd op huidige en nieuwe kennis. In de tussentijd kunnen aanzienlijke verbeteringen aan bepaalde schakels in de keten worden doorgevoerd. Een aantal voorbeelden:

- Optimaal gebruik van machines kan onderhuidse weefselbeschadiging aanzienlijk verminderen;
- In de huidige bewerkingslijnen kan een meer efficiënte planning het gebruik van bunkers verminderen. Hierdoor neemt ook de onderhuidse weefselverkleuring, veroorzaakt door statische belasting en/of transport naar en van bunkers, af;
- Het ontwikkelen van meer flexibele logistieke concepten bevordert het gebruik van de kortste bewerkingsroute;
- Een groot deel van de onderhuidse weefselverkleuring kan worden voorkomen door een adequate beheersing van de knoltemperatuur;
- Bij het bewerken van aardappelen dient zowel het aantal als de intensiteit van belastingen te worden verminderd en het gebruik van bolle botsingslichamen dient zoveel mogelijk te worden vermeden;
- Metingen met een elektronische meetbol zijn nuttig om inzicht te krijgen in de optredende krachten in de keten en om verschillende schakels in de keten met betrekking tot de optredende mechanische belasting te vergelijken.

De in deze studie gehanteerde benadering en de ontwikkelde beoordelingsprotocollen

kunnen ook van toepassing zijn op gelijksoortig onderzoek in andere aardappelproductieketens en productieketens zoals die van bloembollen, fruit, *etc.*. De verkregen kennis kan verder toepassing vinden bij het ontwikkelen van apparatuur, bij het verbeteren van bestaande lijnen en bij het opzetten van nieuwe, meer productvriendelijke bewerkingslijnen en concepten.

Curriculum vitae

Geert-Jan Molema werd geboren op 21 januari 1965 te Winschoten en groeide op op het akkerbouwbedrijf van zijn ouders in Nieuw-Beerta (Gr). Hij volgde achtereenvolgens de MAVO en de HAVO aan de Winschoter Scholen Gemeenschap en sloot laatstgenoemde opleiding af in 1984.

Aansluitend hierop begon hij in 1984 met een opleiding aan de toenmalige Rijks Hogere Landbouw School te Groningen, welke werd afgesloten in 1988. Vervolgens maakte hij met drie medestudenten een rondreis door de Verenigde Staten, Canada en Mexico.

Vanaf 1988 heeft hij zijn opleiding voortgezet aan de toenmalige Landbouw Universiteit te Wageningen met als studierichting landbouwplantenteelt. Zijn afstudeeronderzoek betrof het effect van het temperatuurregime tijdens de groei op de kiemrustduur bij aardappelpootgoed. Daarnaast werd onderzocht welke relaties bestaan tussen knolkenmerken als stolooaanlegdatum en knolaanlegdatum enerzijds en kiemrustduur van individuele knollen anderzijds. In 1991 behaalde hij het ingenieursdiploma. Reeds voordat de opleiding in Wageningen was afgerond aanvaardde hij een functie als wetenschappelijk onderzoeker 'rooibare gewassen' bij het toenmalige Instituut voor Mechanisatie, Arbeid en Gebouwen (thans Instituut voor Milieu- en Agritechniek, IMAG) te Wageningen.

Zijn eerste onderzoekproject betrof een studie naar een alternatief voor chemische loofdoding in aardappelpootgoed, waarbij het onderzoek zich richtte op de methode 'groenrooien en onderdekken'. In 1993 werd begonnen met onderzoek naar beschadiging in aardappelen, dat naar later zou blijken de start was van een promotieonderzoek naar het effect van mechanische belasting op het ontstaan van onderhuidse weefselbeschadiging in aardappelen. De resultaten van dit onderzoek zijn vastgelegd in dit proefschrift.

Thans is hij bij het IMAG wetenschappelijk onderzoeker binnen de afdeling Technologie Open Teelten in de cluster Teelttechnologie en Ketens. Hij doet o.a. onderzoek op het terrein van oogst en handling van aardappelen, precisielandbouw en benutting van ruwvoer door melkvee.