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Changes of water status, elastic properties and blackspot incidence during storage of potato tubers

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Summary

The blackspot bruise susceptibility of potato tubers after mechanical load may change during prolonged storage. Both an increase and a decrease of the occurrence probability of this defect with storage duration have been reported. Increasing blackspot susceptibility has often been related to declining tissue turgor and/or increasing tuber water losses. In the presented study the relationship between elastic properties, water status and blackspot incidence of potato tubers, and its variation during 8 month of storage has been investigated. Tubers of the cultivars 'Afra' and 'Milva' differing in their starch content were stored at 4-5°C in boxes in a practical storage room and in a climate chamber at 4-5°C and 97-100% relative humidity. In spite of a pronounced, mainly water loss-related mass reduction ('Afra': 3.1%, 'Milva': 2.7%) during 5 ½ months in high humidity storage the tuber turgor remained almost stable or even increased under both storage conditions. This turgor maintenance which guarantees vitality of the cells despite the observed water losses may result from elastic adjustment as indicated by a strongly increasing intrinsic volumetric elastic modulus of the inner tuber tissue. The apparent quasi-static modulus of elasticity and the dynamic stiffness of the intact whole tubers from practical storage decreased for both varieties. The blackspot susceptibility of both varieties was subject to strong fluctuations during the duration of storage and no clear relation to any of the measured parameters for water status and elastic properties was identified. In contrast to the general notion blackspot susceptibility was not higher for 'Afra' than for 'Milva' despite the higher starch content of the former.

Introduction

Mechanical stress during harvest and postharvest handling of potato tubers causes visible damages like cracks or shatter bruise and externally invisible dark discolouration of tuber tissue. Many external and produce specific factors may affect the occurrence of these blackspot bruises after mechanical load, e.g. low temperature or low potassium content of the tubers (KUNKEL and GARDNER, 1959; BROOK, 1996; MCGARRY, 1996). One important reason for differences in blackspot susceptibility of cultivars is their dry matter content, which is positively related to specific gravity and starch content (HOFFMANN and WORMANNS, 2001; VAN CANNEYT et al., 2006). This influence of dry matter may be a physical effect because protoplastic membranes are assumed to be more vulnerable after mechanical load when cells contain high amounts of large starch granules (BARITELLE and HYDE, 2003). This multiplicity of potential reasons, their mutual interactions and the diversity of the potato tissue renders the precision of risk assessment for the blackspot incidence still insufficient.

Tissue water status and especially turgor is assumed to be another important factor influencing the susceptibility of potato tubers for external or internal damages. Turgor reduction or loss during storage potentially decreases the risk for external visible damage like splits and cracks (HUGHUES, 1980; SMITTLE et al., 1974). The relation between duration of storage and blackspot susceptibility is often related to changes in turgidity. However, results published up to now are very equivocally.

On the other hand, the probability of blackspot bruising is assumed to increase with the loss of turgidity and the advancing duration of storage (HUGHUES, 1980; SMITTLE et al., 1974; BLAHOVEC and ZIDOVA, 2004). In other reports blackspot susceptibility decreases (DEAN et al., 1993; LAERKE, 2001) or does not change continuously during storage, e.g. increases during the first storage months and decreases later possibly due to beginning sprout growth (KUNKEL and GARDNER, 1959; MOLEMA et al., 1997).

The decrease of potato tuber turgidity during storage is sometimes equated with increasing mass loss (BAJEMA et al., 1998) or described on the basis of measurements of the elasticity of tissue segments, e.g. the measurement of the Young's modulus (MC NABNAY, 1999). The elastic properties may (FALK et al., 1958; MURASE, 1980; LANDAHL et al., 2004) or may not (HERPPICH et al., 2000) depend linearly on tissue turgor.

The aim of this study was to investigate the potential relationship between physiological parameters (mechanical properties (texture) and water status) and the blackspot occurrence of potato tubers, and its variation during 8 month of storage. Furthermore, we used two varieties with contrasting blackspot susceptibility which also differed in their starch content. The presented work is part of research project intending to develop a model to predict the risk of blackspot bruising of potatoes after mechanical loading. It is based on direct impact measurements with a force sensor implanted in the tubers.

Material and methods

Plant material

Potatoes of the floury cultivar 'Afra' and the waxy cultivar 'Milva' from regional production in Brandenburg were hand-harvested in September and October 2007, respectively. Three weeks after harvest starch content of 'Afra' was 17.0 ± 2.2%, of 'Milva' 14.7 ± 1.7% as calculated from specific gravity (MUNZERT et al., 1987), while potassium content was 5.7 ± 0.35 and 0.46 ± 0.46 mg g_{FM}^{-1} (FM = fresh mass).

Two experiments were performed exposing potatoes to different storage conditions:

A. Tubers were stored at 4-5°C in boxes in a practical storage room and their physiological parameters were measured 3 weeks after harvest and later every 8th week until April 2008. The same tubers were used to determine the apparent elastic modulus, stiffness and blackspot bruise susceptibility.

B. Tubers were laid separately on grids in a climate chamber at 4-5°C and 97-100% relative humidity. Water status and mass losses of these tubers were measured at 8 week-intervals from November 2007 to April 2008.

Physiological properties of inner tuber tissue

Water status and total soluble solids

Water potential was measured psychrometrically (VON WILLERT et al., 1995) using 10 C-52 dew point hygrometer chambers connected to a HR-33T micro voltmeter via a PS-10 switchbox (all Wescor Inc., Logan, USA) on tissue discs (6 mm diameter and 2 mm thick), obtained from the middle of the tuber with a cork borer. Subsequently, fresh mass of the discs was determined with an electronic balance (BP 210 S, Sartorius AG, Göttingen, Germany). Then, the discs were allowed to transpire freely for 30 min, and water potential and fresh mass were measured again after this time.

Finally, samples were put into a 1.5 ml micro test tube (Eppendorf AG, Hamburg, Germany), frozen, thawed, centrifuged for 3 min (14000xg, MiniSpin® plus, Eppendorf AG, Hamburg, Germany). The supernatant was analysed for its molal osmotic content (c_{osm}) with a vapour pressure osmometer (VAPRO 5520, Wescor Inc., Logan, USA) and for its total soluble solids content (TSS) with a digital refractometer (ATAGO PR 1, Leo Kuebler GmbH, Karlsruhe, Germany). Pressure potential (Ψ_P) or turgor was calculated from the difference of water potential and osmotic potential (Ψ_π). The latter was calculated from the osmotic content using the van't Hoff's relation ($\Psi_\pi = c_{osm} * R * T$; c.f. VON WILLERT et al., 1995). Finally dry mass (DM) of the tissue discs was obtained after oven-drying at 85°C (24 hours) and their water content was calculated from fresh and dry mass.

According to LANDAHL et al. (2004) the volumetric modulus of elasticity (ε, c.f. VON WILLERT et al., 1995) of the tissue samples was calculated from the changes in pressure potential and fresh mass during the two subsequent measurements multiplied by the initial fresh mass (FM_i) as

$$\varepsilon = \frac{\Delta\Psi_P}{\Delta FM} FM_i$$

This volumetric modulus of elasticity describes the relationship between changes in cell water content and in cell pressure potential and their interaction with cell wall elastic properties. It is hence largely independent of a variation of the overall structure of the object under investigation.

Physiological properties of whole potato tubers

Apparent modulus of elasticity

The apparent modulus of elasticity (E) of 40 entire potato tubers was determined by a non-destructive quasi-static compression test (v = 10 mm min^{-1}) using an universal testing machine (Zwicki 1120, Zwick, Ulm, Germany) with a spherical steel body (diameter 12.7 mm). During the measurements the tubers were held in a tray filled with sand. Each tuber was measured twice at its equator (Fig. 1). According to the formula given by ASAE (1999) E (MPa) was calculated from the deformation (D) at a maximum force (F) of 4 N as

$$E = \frac{0.531 \times F \times (1-\mu)}{D^{1.5}} \times \left(\frac{2}{R} + \frac{4}{d}\right)^{0.5}$$

μ = Poissons-ratio = 0.49 (MOHSENIN, 1986)
d = diameter steel body of 12.7 mm
R = radius of the tuber at the measuring position

Acoustic stiffness

The acoustic impulse response method was applied to analyse the stiffness of the potato tubers. A little hammer with a small steel body was used to strike the tubers at the same 2 positions as used for measurements of the apparent modulus of elasticity. The resulting sound was recorded with a microphone connected to a computer (Fig. 1). Measurements were repeated 5 times at each position. The mean frequencies at the first local maximum (*f*) of the frequency spectrum, obtained after a fast Fourier transformation of the raw sound signal, and the respective tuber fresh mass (*FM*)) was used to calculate the stiffness factor (*S*) as

$$S = f^2 \times FM^{\frac{2}{3}}$$

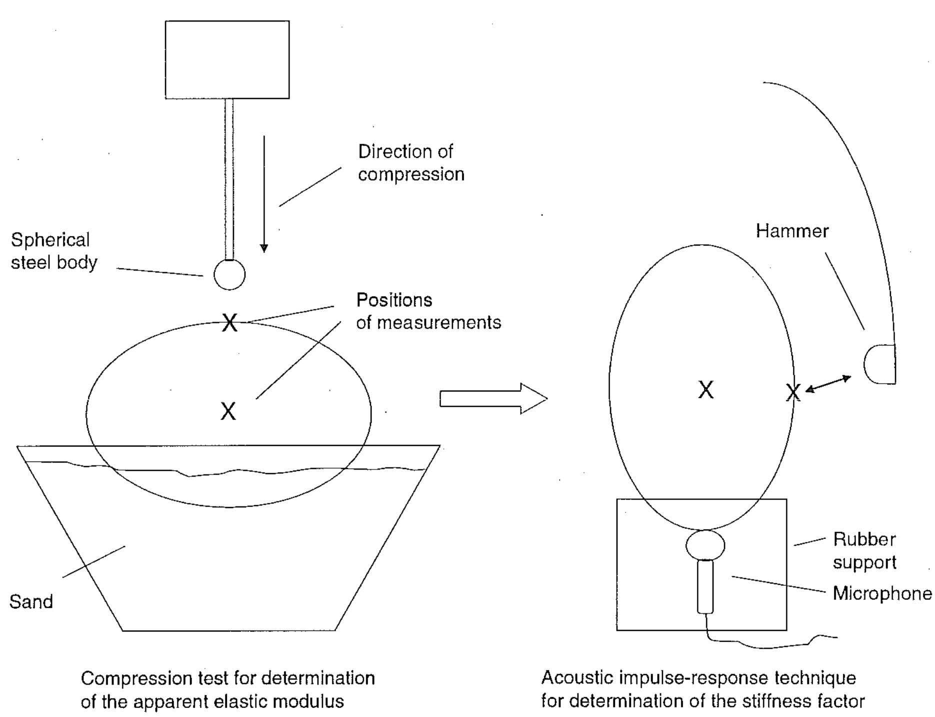

Fig. 1: Schema of the two different measuring equipments for the non-destructive determination of elasticity properties of potato tubers.

Mass loss

Thirty potato tubers (trial B) were weighed every 8 weeks individually and percentage of average mass loss was calculated.

Determination of blackspot bruise susceptibility

Drop tests have been carried out to determine blackspot susceptibility by using a fall apparatus. The tubers were oriented with their apical end faced down and dropped once from 50 cm onto a flat steel plate equipped with an impact force sensor. Then the potatoes were stored at 33°C and 95 % relative humidity for 48 h, and rating of internal damage was carried out thereafter. For this, the potato tubers were cut into two halves at the loaded position and an image of the cut surface was taken. The dimensions of blackspot bruises were determined by the image analysis software Optimas 6.0™ (BioScan Inc., Bothell Washington, USA). Bruise susceptibility was rated in two different ways:

1. Calculation of the percentage (P) of the number of damaged tubers (a) from all 40 dropped samples (b):

$$P = \frac{a}{b} \times 100$$

P = percentage of damaged tubers [%]
a = number of damaged tubers
b = total number of dropped tubers (n=40)

2. Average value of a blackspot index as indicated in Tab. 1.

Tab. 1: Blackspot index for evaluation of internal damage at the loaded position of single potato tubers

Dimension of the dark spot (cm^2)	Blackspot index
No damage	1
> 0 - 0.5	2
> 0.5 - 1	3
> 1 - 1.5	4
> 1.5 - 2	5
> 2	6

Statistical analysis

Data were analysed by analysis of variance (ANOVA) with the GLM procedure (SAS version 9.1, 2002) to determine the influence of variety and storage duration and the means were compared by the Tukey-Test ($P < 0.05$).

Results

Physiological properties of tuber tissue

Water status and weight loss

During the whole storage period water potential of 'Milva' tubers decreased more or less continuously. This decline was almost doubled in tubers stored under practical conditions (Fig. 2 A) than in high humidity (Fig. 2 D). Changes in water potential of 'Afra' tubers were always less pronounced under both storage conditions.

Except for 'Milva' in practical storage osmotic potential of the tubers was nearly constant until December (Fig. 2 B) and January (Fig. 2 E), respectively, but decreased afterwards. Under both storage conditions osmotic potential of 'Afra' tubers was significantly higher than that of 'Milva'.

Mean tissue turgor of 'Milva' tubers was significantly higher than that of 'Afra', irrespective of storage conditions which obviously had no effects on this tissue property (Fig. 2C and F). While pressure potential was more or less constant in 'Milva' tubers at 0.44±0.03 MPa (average for both storage conditions), it increased by 0.11 MPa in those of 'Afra' during the last 8 storage weeks. Interestingly pressure potential of 'Afra' tubers stored at high humidity increased despite a continuous mass (water) loss from November until April which was finally larger for 'Afra' (3.1 %) than for 'Milva' (2.7 %) (Fig. 2G).

Volumetric modulus of elasticity

The volumetric elastic modulus of 'Afra' and 'Milva' tubers tended to decrease initially after harvest and increased strongly during late storage in April (Fig. 3). The final volumetric modulus of elasticity (average of both cultivars) was about 20 % higher at the high air humidity storage than under practical storage conditions (Fig. 3).

Water content and soluble solids

Tissue water content based on dry matter of 'Milva' tubers was significantly higher than of those of 'Afra' in high humidity storage. It decreased in tubers of both varieties from initial to late storage under both conditions by 3 to 4g/g DM (Tab. 1). Irrespective of the storage conditions total soluble solid contents (TSS) of 'Milva' tubers were significantly higher than those of 'Afra'. TSS increased during late storage in tubers of both varieties and at both storage humidities. The dry based matter osmotic contents were significantly higher for 'Milva' than for 'Afra' and in both storage methods they were higher in the first storage months than in spring.

Physiological properties of whole potato tubers

Elastic properties

Both the quasi-static modulus of elasticity and the dynamic stiffness factor decreased with storage in tubers of both cultivars (Fig. 4). Although fresh tubers of 'Afra' were significantly stiffer, i.e. they had higher E and S than those of 'Milva' they tended to be slightly more elastic during the rest of the experiment.

Blackspot bruise of tubers after mechanical load was not different between 'Afra' and 'Milva'. Tubers of both cultivars showed the highest susceptibility in December (Fig. 5).

Discussion

Water status and mechanical properties of potato tubers

The results of the simultaneous measurement of mass losses and changes in pressure potential of potato tubers stored in high humidity showed that long-term variations of these parameters are independent of each other (HERPPICH et al., 2001a). Relative mass losses and, hence, water losses continuously increased up to 2.7 % ('Milva') and 3.1 % ('Afra'), respectively, whereas pressure potential either remained more or less constant or even increased slightly. The range of potato tuber water potential and pressure potential is similar to results published by LAERKE (2001) for the varieties 'Dali' and 'Oleva'. He observed a similar decline in water potential from -0.6 to -0.8 MPa during 6 month of storage but in contrast to our experiments he also reported a decline in pressure potential from 0.4 to 0.2 MPa.

Considering the average rates of CO_2-release of tubers from the presented study (data not shown) of 2.5 mg kg^{-1} h^{-1} ('Afra') and 2.9 mg kg^{-1} h^{-1} ('Milva'), respectively, during the whole storage, respiration of organic substances contributed by 26% to the final total mass losses in both varieties. Therefore, true water losses were significantly lower than total mass losses, yielding 2.4 % and 1.9 % of the initial fresh mass for 'Afra' and 'Milva', respectively. Furthermore, the nearly

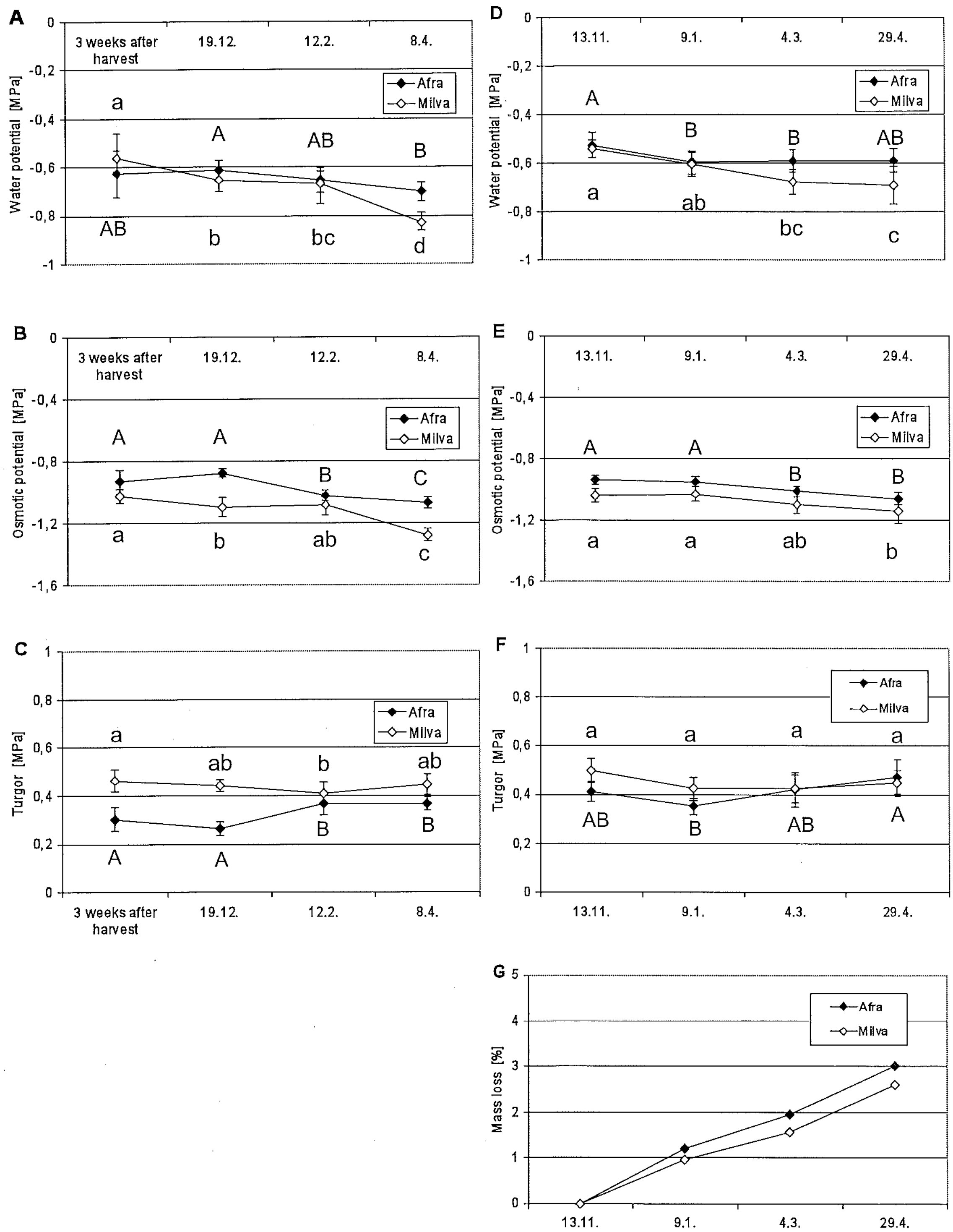

Fig. 2: Means (± SD; n = 8) of water potential (A, D), osmotic potential (B, E) turgor (C, F) and mass loss (G) of potato tubers stored at 4 to 5°C (A-C) without air humidity control, i.e. under practical conditions, and at high humidity (97-100 %) in a climate chamber (D-G). Letters in capitals indicate significant differences for 'Afra' and those in lower case letters for 'Milva'.

negligible decline in water potential and the relative constancy of pressure potential clearly highlights that the simply measuring relative mass losses is not a true and adequate indicator of physiological relevant changes in tissue water status.

Maintenance of tuber pressure potential in spite of these water losses may result from either osmotic adjustment (HERPPICH et al., 2001a; b) or elastic adjustment (WEISZ et al., 1989; NEUMANN, 1995), two different mechanisms which can be induced in plant tissue by drought stress to guarantee vitality of cells. During elastic adjustment, as indicated by the increase in the volumetric elastic modulus during late storage in spring, cell walls can harden i.e. stiffness and strength of the cell walls increase (NEUMANN, 1995; HERPPICH et al., 2001a, b) possibly either due to enhanced cell wall thickness (MARSHALL and DUMBROFF, 1999), by incorporation of proteins into cell wall by

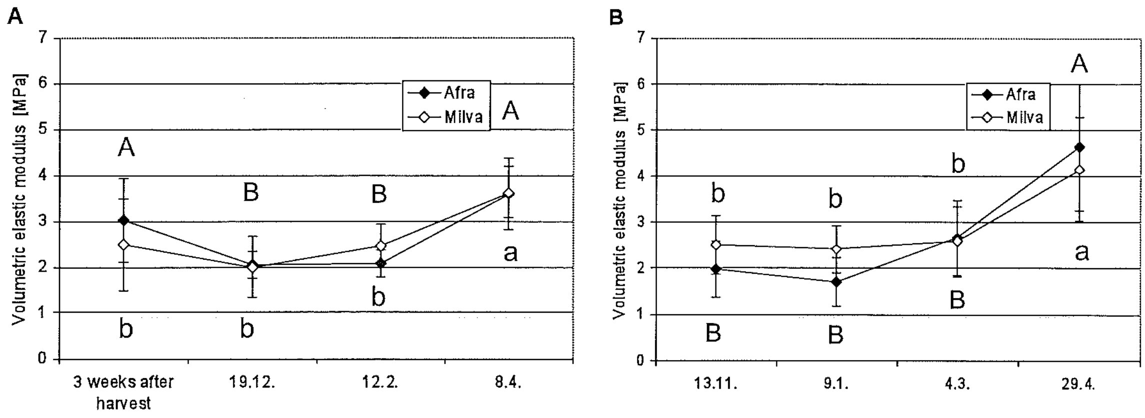

Fig. 3: Volumetric modulus of elasticity (means ± SD; n = 8) of potato tubers stored at 4 to 5°C (A) without air humidity control, i.e. under practical conditions, and (B) at high humidity (97-100 %) in a climate chamber. Letters in capitals indicate significant differences for 'Afra' and those in lower case letters for 'Milva'.

Tab. 1: Water content, total soluble solids and osmotic contents of potato tuber tissue stored at 4 to 5°C (A) without air humidity control, i.e. under practical conditions, and (B) at high humidity in a climate chamber (97-100 %). Letters in capitals indicate significant differences for 'Afra' and those in lower case letters for 'Milva'.

	A				B			
Water content [g g^{-1} DM]								
	3 weeks after harvest	19.12.	12.2.	8.4.	13.11.	9.1.	4.3.	29.4.
'Afra'	7.55 A	5.64 AB	3.54 B	3.87 B	5.82 A	7.10 A	3.18 B	3.79 B
'Milva'	7.19 a	7.59 a	3.84 b	4.85 b	8.58 a	8.86 a	4.30 b	4.77 b
Total soluble solids [%]								
'Afra'	4.4 B	4.0 B	4.5 AB	5.2 A	3.9 B	4.1 B	4.6 A	4.6 A
'Milva'	4.9 b	5.3 b	5.1 b	7.2 a	4.9 b	4.7 b	5.2 ab	5.8 a
Osmotic contents [mol g^{-1} DM]								
'Afra'	2.3 A	1.7 AB	1.2 B	1.4 B	1.9 AB	2.3 A	1.1 C	1.4 BC
'Milva'	2.5 a	2.8 a	1.4 b	2.1 ab	3.0 a	3.1 a	1.6 b	1.8 b

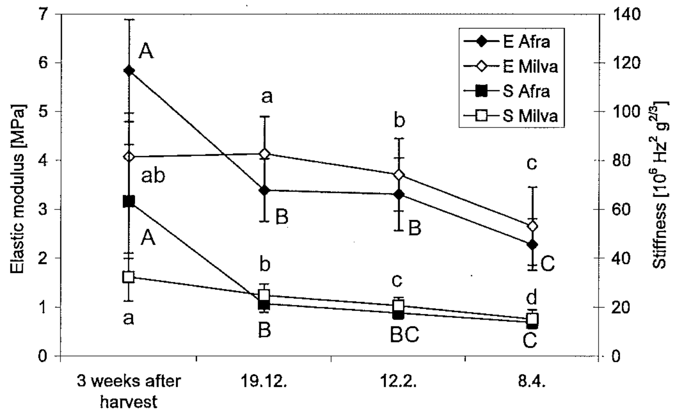

Fig. 4: Elastic modulus (E) and stiffness factor (S) measured on whole potato tubers during storage under practice conditions (T = 4-5°C; no air humidity control). Letters in capitals indicate significant differences for 'Afra' and those in lower case letters for 'Milva'.

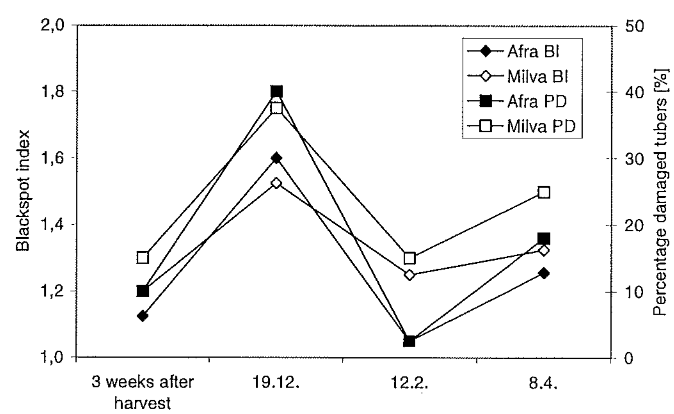

Fig. 5: Blackspot index (BI) and percentage of tubers (PD) with blackspot bruise after fall from 50 cm on steel (trial A)

oxidative cross linking (MARSHALL et al., 1999) and/or changes in the pectin composition during storage (VAN DIJK et al., 2002). According to SCHULTE (1992) water relation and water storage theory implies that stiffer cell walls may lead to enhanced water uptake and water conservation at the risk of reduced water potential and pressure potential. However, this was certainly not the case in the stored potato tubers. On the other hand, it has been repeatedly shown that elastic adjustment due to a decrease in tissue elasticity can help maintaining pressure potential (FAN et al., 1994; MARSHALL and DUMBROFF, 1999; HERPPICH et al., 2001a). In senescent cells water uptake has a stronger effect on pressure potential than in young more elastic cells (VON WILLERT et al., 1995).

The fact, that water potential rather closely followed the changes in osmotic potential suggests that osmotic adjustment may also play an important role in stored potato tubers. Osmotic adjustment as indicated by a net increase in the effective concentration of osmotic active substances thus decreasing the osmotic potential of the cell sap independent of any changes in cell water volume (VON WILLERT et al., 1995). Although the variations in total soluble solute contents may indicate a water volume independent net increase in osmotic active substance, most probably free reducing sugars, the calculation of dry matter based and, hence, water volume independent content of osmotic substances does not confirm this assumption. In contrast total osmotic contents decreased from autumn to spring.

On the other hand, it has been shown manifold that plants can actively reduce the maximum cell volume via physiological adjustment of cell wall properties to guarantee turgor maintenance at increasing water deficits (LEVITT, 1986; MARSHALL and DUMBROFF, 1999). These potential changes in cell wall mechanical properties may be well reflected by the observed increase in the volumetric modulus of elasticity. Hence, this assumed active control of cellular water volume can help to understand the demonstrated clear maintenance of tissue water status despite continuous water losses.

The observed increase in bulk volumetric modulus of elasticity of core tissue is obviously in contrast with the more or less continuous decline of both apparent quasi-static elastic modulus and the dynamic stiffness factor, both obtained on whole potato tubers. It might be that variations in mechanical properties are highly tissue-specific. Starch might be an important factor influencing mechanical properties of potato tubers (VAN DIJK et al., 2002). Starch is particularly localised in the outer zone of potato tubers (SCHICK and KLINKOWSKI, 1961). Hence, the decrease in the apparent elastic modulus might be at least partially due to the degradation of starch and its conversion into soluble sugars in spring (NOURIAN et al., 2003; GOTTSCHALK and EZEKIEL, 2006).

It is also probable that the cortex tissue below the periderm, which has been directly compressed during the measurement of the quasi-static apparent elastic modulus had a lower water content towards the end of storage than the perimedullary tissue from the tuber core used for determination of pressure potential and volumetric elastic modulus. However, comprehensive measurements of tuber water status did not show any gradient from outer to inner tissue (data not shown). Furthermore, SOLOMON and JINDAL (2007) reported a similar increase in potato elasticity during the course of storage using axial compression tests on cylindrical (3 x 1.5 cm) tissue specimen. And, as is the case in the presented investigation, compression test and the acoustic response techniques, which truly yields a produce-averaged value (CHEN, 1996), give very similar results under many conditions and with very different produce (LANDAHL et al., 2004; HERPPICH et al., 2005). Hence, tissue-specifity seems not to be meaningful explanation for the observed differences.

Furthermore, physiologically regulated processes like elastic adaptation occurring during long-term storage must be differentiated from short-term effects on tissue elastic properties simply due to changes in water status. It has been shown in radish tubers that under such conditions the volumetric elastic modulus and both the apparent elastic modulus and the stiffness factor yield very similar results (LANDAHL et al., 2004), except for fully hydrated produce. Consequently, a close linear dependence of the Young's modulus on pressure potential or water potential can be found if the potato tissue water status is rapidly and artificially changed by immersing the tissue in hyper- or hypo-osmotical solutions (FALK et al., 1958; NILSSON et al., 1958; MURASE et al., 1980). This all may indicate that both the apparent modulus of elasticity and the stiffness coefficient are closely related to the water volume of the studied object. Hence, any variation of these parameters simply reflects short-term and long-term changes in water mass irrespective of structural and physiological adaptation. In contrast, the volumetric elastic modulus directly describes the elastic properties of thin-walled plant tissue highly sensitive to physiological effects (COSGROVE, 1988).

A strong effect of the osmotically induced variation of pressure potential on the tissue fracture toughness of potato tissue can also be found (LAZA et al., 2001). However, it had been shown that this method to rapidly adjust tissue water status introduces interfering artificial effects (BAJEMA et al., 1998). Hence, the behaviour of tubers dehydrated by controlled storing at varying air humidity to obtain different mass losses must be differentiated from results obtained by tissue soaking. Naturally dehydrated tubers showed increasing failure strain and decreasing shock wave speed with reduced water content (BAJEMA et al., 1998).

Physiological properties and susceptibility to damage

Tubers of 'Milva' stored under practical conditions showed a 0.12 ± 0.06 MPa higher pressure potential than those of 'Afra'. This might be a reasonable cause for the higher disposition to superficial crack formation after mechanical impact as observed for tubers of 'Milva' (data not shown). Indeed, van CANNEYT et al. (2006) reported that high pressure potential may lead to tissue cracks in practice similar to observations that increased turgidity increases the susceptibility of carrots to mechanical damage (KOKKORAS, 1995).

The blackspot susceptibility is influenced by biochemical but also physical properties of potato tissue such as cell wall strength, cell flexibility, tuber turgor, cell sap viscosity and tissue stiffness. Potassium deficiency which leads to a high blackspot susceptibility causes low pressure potential and reduced stiffness (MCNABNAY et al., 1999). VAN CANNEYT et al. (2006) conclude from a study of the influence of specific gravity and temperature on stiffness of potato tubers that cell structures with a high pressure potential form a more coherent unity, in which the cells protect each other against impacts. Therefore, it has been recommended that storage and handling temperature should be relatively high and specific gravity of the potatoes low in combination with a moderate to high pressure potential to create elastic cell walls and membranes in combination with a stiff coherent tissue structure to reduce discolouration and blackspot. In addition, LAERKE (2001) reported that a decline in turgor pressure of stored potato tubers was accompanied by decreased blackspot susceptibility.

However, in our study, actual blackspot susceptibility was highly variably while measured pressure potential was almost constant throughout the duration of storage. Hence, no meaningful correlation between these two parameters could be obtained.

Furthermore, tubers of both potato cultivars showed highest elastic modulus and, thus, stiffness directly after harvest in autumn when the lowest blackspot susceptibility was observed. The decrease in stiffness from February to April was accompanied by an increasing percentage of damaged tubers after mechanical impact.

HEMMAT (1987) showed that the severity of tissue bruising is related to the elastic modulus of potato tubers. For tubers with a low elastic modulus greater maximum normal strain, i.e. deformation, and damage occur when the tuber tissue is loaded at a given energy in comparison with tubers with a high elastic modulus. LAZA et al. (2001) explain a slightly decreasing tissue toughness of stored potatoes with a loss of cell membrane integrity. This might be reasons for increasing blackspot susceptibility in spring also observed by other authors (HUGHUES, 1980; SMITTLE et al., 1974).

We did not find an explanation for the high blackspot susceptibility observed in December for both cultivars. MURFIT and OBOBI (1980) presume that varying bruise incidence after different storage duration can be caused by low or high static load on the tubers in bulk storage. Regarding our study this can not be an explanation for the high blackspot susceptibility in December, because static load was higher for the tuber samples in spring. Maybe physiological changes related to dormancy which have not been considered in this study have an influence of blackspot occurrence after mechanical load. MOLEMA et al. (1997) supposed that a strong decline in discolouration susceptibility from 5 to 7 month storage is caused by the beginning of sprout growth.

In contrast to the general notion blackspot susceptibility of 'Afra' was not higher than of 'Milva' despite a higher starch content of the former. In this study potato tubers were loaded exclusively at their apical end. Maybe cultivar specific differences in the occurrence of internal discolouration are more pronounced after mechanical impact at the older stem end, render it more susceptible than the apical end (KUNKEL and GARDNER 1959).

Conclusion

According to the presented results neither turgor nor elasticity of potato tubers are closely related to blackspot bruise incidence after mechanical load. Presumably, it is necessary to additionally consider biochemical changes in order to explain the changing blackspot susceptibility during storage. In this context the induction of sprout growth which occurred in February for 'Milva' and later in April for 'Afra' may play an important role.

Acknowledgments

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References

ASAE, 1999: Compression test of food materials of convex shape. ASAE Standards, Standards engineering practices data, 46th edition, 570-575. ASAE, St. Joseph, MI, USA.

BAJEMA, R.W., HYDE, G.M., BARITELLE, A.L., 1998: Turgor and temperature effects on dynamic failure properties of potato tuber tissue. T. ASAE 41, 741-746.

BARITELLE, A.L., HYDE, G.M., 2003: Specific gravity and cultivar effects on potato tuber impact sensitivity. Postharv. Biol. Technol. 29, 279-286.

BROOK, R.C., 1996: Potato Bruising, How and why emphasizing black spot bruise. Running Water Publishing, Haslett, Michigan.

BLAHOVEC, J., ZIDOVA J., 2004: Potato bruise spot sensitivity dependence on regimes of cultivation. J. Agric. Eng. Res. 50, 89-95.

CHEN, P., 1996: Quality evaluation technology for agricultural products. Proceedings of the International Conference on Agricultural Machinery Engineering (Vol. 1), Seoul, Korea, November 12-15, 171-204.

COSGROVE, D.J., 1988: In defence of the cell volumetric elastic modulus. Pl. Cell Environm. 11, 67-69.

DEAN, B.B., JACKOWIAK, N., NAGLE, M., PAVEK, J., CORSINI, D., 1993: Blackspot pigment development of resistant and susceptible *Solanum tuberosum* L. genotypes at harvest and during storage measured by three methods of evaluation. Amer. Potato J. 70, 201-217.

FAN, S., BLAKE, T.J., BLUMWALD, E., 1994: The relative contribution of elastic and osmotic adjustments to turgor maintenance of woody species. Physiol. Pl. 90, 408-413.

FALK, S., HERTZ, C.H., VIRGIN, H.I., 1958: On the Relation between Turgor Pressure and Tissue Rigidity. I. Physiol. Pl., 802-817.

GOTTSCHALK, K., EZEKIEL, R., 2006: Storage. In: Gopal, J., Khurana, S.M.P. (eds.), Handbook of Potato production, improvement and postharvest management, 489-517. Harworth Press, Oxford, UK.

HEMMAT, A., 1987: Stress/strain analysis and internal bruising in potato tubers. Ph.D Thesis, Cranfield Institute of Technology Silsoe College, Bedford.

HERPPICH, W.B., MEMPEL, H., GEYER, M., 2000: Interactive effects of mechanical impacts, temperature and humidity on water relations and tissue elasticity of stored carrots. J. Appl. Bot. 74, 271-276.

HERPPICH, W.B., MEMPEL, H., GEYER, M., 2001a: Osmotic and elastic adjustment, and product quality in cold-stored carrot roots (*Daucus carota* L.). Gartenbauwissenschaft 66, 20-26.

HERPPICH, W.B., MEMPEL, H., GEYER, M., 2001b: Drought- and low temperature-acclimation in carrot (*Daucus carota* L.) roots. J. Appl. Bot. 75, 138-143.

HERPPICH, W.B., HUYSKENS-KEIL, S., KADAU, R., 2005: Effects of short-term low-temperature storage on mechanical and chemical properties of white Asparagus cell walls. J. Appl. Bot. Food Qual. 79, 63-71.

HOFFMANN, T., WORMANNS, G., 2001: Determination of material characteristics of potatoes regarding processing and consumption – impact stress and tendency to develop black spots. Proceedings of the 6th International Symposium Fruit, Nut, and Vegetable Production Engineering, Potsdam, 11.-14.09.2001, 397-401.

HUGHUES, J.C., 1980: Role of tuber properties in determining susceptibility of potatoes to damage. Ann. Appl. Biol. 96, 344-345.

KOKKORAS, I.F., 1995: The effect of temperature and water status of carrot tissue on residual strains and stresses. Acta Hort. 379, 491-498.

KUNKEL, R., GARDNER, W.H., 1959: Black Spot of Russet Bank Potatoes. Proc. Amer. Soc. Hort. Sci. 73, 436-444.

LAERKE, P.E., 2001: Blackspot bruise in potato tubers. Dissertation, The Royal Veterinary and Agricultural University Copenhagen.

LANDAHL, S., HERPPICH, W.B., HEROLD, B., GEYER, M., DE BAERDEMAEKER, J., 2004: A Comprehensive Evaluation of the Interactions between Produce Elasticity and Water Status. Eur. J. Hort. Sci. 69, 250-257.

LAZA, M., SCANLON, M.G., MAZZA, G., 2001: The effect of tuber pre-heating temperature and storage time on the mechanical properties of potatoes. Food Res. Int. 34, 659-667.

LEVITT, J., 1986: Recovery of turgor by wilted, excised cabbage leaves in the absence of water uptake. A new factor of drought acclimation. Plant Physiol. 82, 147-153.

MARSHALL, J.G., DUMBROFF, E.B., 1999: Turgor regulation via cell wall adjustment in white spruce. Pl. Physiol. 119, 313-39.

MARSHALL, J.G., DUMBROFF, E.B., THATCHER, B.J., MARTIN, B., RUTLEDGE, R.G., BLUMWALD, E., 1999: Synthesis and oxidative insolubilization of cell-wall proteins during osmotic stress. Planta 119, 313-39.

MCGARRY, A., HOLE, C.C., DREW, R.L.K., PARSONS, N., 1996: Internal damage in potato tubers: a critical review. Postharv. Biol. Technol. 8, 239-258.

MCNABNAY, M., DEAN, B.B., BAJEMA, R.W., HYDE, G.M., 1999: The effect of potassium deficiency on chemical, biochemical and physical factors commonly associated with blackspot development in potato tubers. Amer. J. Potato Res. 75, 53-60.

MOHSENIN, N.N., 1986: Physical properties of plant and animal materials. Second updated and revised edition. Gordon and Breach Science Publishers, New York, USA.

MOLEMA, G.J., VERWIJS, B.R., VAN DEN BERG J.V., BRETELER, H., 1997: Effect of repetitive impacts on subcutaneous tissue discoloration in potato tubers. Netherlands J. Agric. Sci. 45, 187-200.

MUNZERT, M., SCHWEITZER, E., VOIT, K., 1987: Eine Stärkewaage mit variabler Einwaage und Datenspeicherung. Kartoffelbau 10, 377-380.

MURASE, H., MERVA, G.E., SEGERLIND, L.J., 1980: Variation of Young's modulus of potato as a function of water potential. T. ASAE 23, 794-796, 800.

MURFIT, R.F.A., OBOBI, A.A., 1980: Delayed bruise development in potato tubers. Ann. Appl. Biol. 96, 354.

NEUMANN, P.M., 1995: The role of cell wall adjustment in plant resistance to water deficits. Crop Sci. 35, 1258-1266.

NILSSON, S.B., HERTZ, C.H., FALK, S., 1958: On the relation between turgor pressure and tissue rigidity. 2. Theoretical calculations on model systems. Physiol. Plant. 11, 818-837.

NOURIAN, F., RAMASWAMY, H.S., KUSHALAPPA, A.C., 2003: Kinetics of quality changes associated with potatoes stored at different temperatures. Lebensm. Wiss. Technol. 36, 49-65.

SCHICK, R., KLINKOWSKI, M., 1961: Die Kartoffel, VEB Deutscher Landwirtschaftsverlag, Berlin.

SCHULTE, P.J., 1992: The units of currency for plant water status. Pl. Cell Environm. 15, 7-10.

SMITTLE, D.A., THORNTON, R.E., PETERSON, C.L., DEAN, B.B., 1974: Harvesting potatoes with minimum damage. Amer. Potato J. 51, 152-164.

SOLOMON, W.K., JINDAL, V.K., 2007: Modelling changes in rheological properties of potatoes during storage under constant and variable conditions. Lebensm. Wiss. Technol. 40, 170-178.

VAN CANNEYT, T., DIERICKX, W., VERSCHOORE, R., RAMON, H., SONCK, B., 2006: Effect of Pre-load, Vibration Frequency, Temperature and Specific Gravity of Potato Tissue on Visco-elastic Vibration Damping and Complex Modulus Properties. Biosys. Eng. 94, 415-427.

VAN DIJK, C., BEEKHUIZEN, J.G., GIBCENS, T., BOERIU, C., FISCHER, M., STOLLE-SMITS, T., 2002: Texture of Cooked Potatoes (*Solanum tuberosum*). 2. Changes in Pectin Composition during Storage of Potatoes. J. Agric. Food Chem. 50, 5089-5097.

VON WILLERT, D.J., MATYSSEK, R., HERPPICH, W.B., 1995: Experimentelle Pflanzenökologie, Grundlagen und Anwendungen. Georg Thieme Verlag, Stuttgart.

WEISZ, P.R., RANDALL, H.C., SINCLAIR, T.R., 1989: Water relations of turgor recovery and restiffening of wilted cabbage leaves in the absence of water uptake. Pl. Physiol. 91, 433-439.

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