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A Comprehensive Evaluation of the Interactions between Produce Elasticity and Water Status

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Summary

Texture is an important quality parameter in fresh horticultural products. However, its complexity and variability entails that instrumental analyses describe it only partial whereas various properties are involved. For example, product water status, cell wall physical properties and tissue structure interdependently determine compressive and tensile strength, and elastic properties, which all together characterise texture. Furthermore, short-term effects on texture under unfavourable conditions during shelf live may be functionally different from those occurring during long-term storage. During recent years, new methods such as the acoustic impulse-response technique have become available to non-destructively analyse the elastic texture components. In addition, water potential, osmotic potential and turgor can be non-destructively assessed with the pressure bomb in combination with pressure volume analyses in many products. An experiment was designed to comprehensively study the effects of water status on different tissue elastic parameters. Water potential (Ψ), fresh mass, apparent elastic modulus (E, quasi-static compression test), and stiffness factor (S, acoustic impulse-response test) were repeatedly determined on radish tubers during desiccation by free transpiration. E showed a two-phased linear relationship with Ψ. At water potentials beyond the turgor-loss-region, the slope of this relationship largely declined. In turgescent tubers a considerable part of the variation of E could be explained by water potential. S showed a less clear two-phased relation and wilting seems to exhibit only minor effects on stiffness. Both E and S increased linearly with pressure potential but S showed a weaker correlation with turgor. While the decline in acoustic stiffness with increasing relative water deficit seemed to follow an exponential model, the correlation between E and RWD could be best described by a power function. E and S increased with increasing volumetric modulus of elasticity (ε) in a curvilinear manner. When E and S were compared directly, a curvilinear correlation was found. These results show that S is a good indicator for changes in produce water content. Both parameters are useful to indicate postharvest texture changes. However, the results point toward the possibility that S is less related to short-term changes of product rigidity than E.

Zusammenfassung

Eine umfassende Beurteilung der Wechselwirkungen zwischen Produktelastizität und Wasserzustand. Bei frischen gartenbaulichen Produkten ist die Textur ein wichtiger Qualitätsparameter. Allerdings beinhaltet der Texturbegriff eine Vielzahl von unterschiedlichen Produkteigenschaften. Diese Vielschichtigkeit bedingt, dass eine objektive instrumentelle Analyse immer nur einen Teilaspekt der Produkttextur erfassen kann. So bestimmen der Wasserzustand, die physikalischen und chemischen Zellwandeigenschaften und die Gewebestruktur interaktiv die Druck- bzw. Zugfestigkeit und die elastischen Eigenschaften eines Produktes. Diese Größen wiederum bestimmen in erster Linie die Textur. Kurzzeitige Änderungen der Textur, wie sie etwa durch ungünstige Bedingungen beim Transport und im Verkauf hervorgerufen werden, können sich funktionell von solchen Veränderungen unterscheiden, wie sie in der Langzeitlagerung auftreten. In den letzten Jahren wurden neue Methoden wie etwa die akustische „impuls-response"-Technik verfügbar, die eine zerstörungsfreie Analyse der elastischen Texturkomponente ermöglichen. Wasserpotential, osmotisches Potential and Turgor lassen sich bei vielen Produkten mit Hilfe der Druckbombenmethode in Kombination mit Druck-Volumen-Analysen ebenfalls nichtdestruktiv erfassen. Mit diesen Ansätzen wurde ein Experiment konzipiert, das eine umfassende Untersuchung des Einflusses des Wasserzustandes auf verschiedene Gewebeelastizitätsparameter erlaubt. Wasserpotential (Ψ), Frischmasse, scheinbarer Elastizitätsmodul (E, quasi-statischer Kompressionstest) und Steifheitsfaktor (S, akustische „impuls-response"-Test) wurden wiederholt an Radieschen bestimmt, die bei freier Transpiration kontinuierlich austrockneten. E zeigte dabei eine zweiphasige, lineare Abhängigkeit vom Wasserpotential. Nach Unterschreiten des Welkepunktes verringerte sich die Steigung dieser Beziehung drastisch. Bei turgeszenten Knollen lässt sich die Variation von E primär auf die Änderung des Wasserpotentials zurückführen. S zeigte eine weniger deutlich ausgeprägte zweiphasige Beziehung wobei Welken nur einen geringen Einfluss auf den dynamischen Steifheitsfaktor auszuüben scheint. Sowohl E als auch S nehmen linear mit dem Druckpotential zu, jedoch ist die Korrelation zwischen S und dem Turgor deutlich schwächer. Während die Abnahme des

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dynamischen Steifheitsfaktors mit zunehmendem relativen Wasserdefizit (*RWD*) offensichtlich einem exponentiellen Modell folgt, lässt sich die Korrelation zwischen *E* und *RWD* am besten mit einer Potenzfunktion beschreiben. Sowohl *E* als auch *S* zeigen eine nichtlineare Beziehung mit dem volumetrischen Elastizitätsmodul (ε). Zwischen *E* und *S* besteht eine enge aber ebenfalls nichtlineare Korrelation. Die vorgestellten Ergebnisse verdeutlichen, dass *S* einen guten Indikator der Veränderungen des Produktwassergehaltes darstellt. Sowohl *E* als auch S sind wertvolle Parameter zur Bestimmung von Texturänderungen in der Nachernte. Allerdings deuten die Ergebnisse auch darauf hin, dass *S* ein schlechterer Indikator schneller Änderungen der Produktsteifigkeit ist als *E*.

Introduction

Texture is an essential attribute of quality for fruits and vegetables. It comprises the sum of physical, organoleptic and auditory properties arising from the structure of food that humans can detect with their senses (ROSENTHAL 1999). The detection of texture also depends on the psychological state of the human. Thus, texture analysis relates objective instrumental measurements to subjective consumer sensation (HARKER et al. 1997; SCHOTTE et al. 1999). Textural produce properties change during maturation and ripening (TONG et al. 1999), and during senescence or decay in storage (TU et al. 2000) and during display in retail (HERPPICH et al. 2001a, b).

Objectively, product texture can be described by firmness (MOHSENIN 1986), i.e. compressive and fracture strength (VINCENT 1990) or tensile strength (TU 1998), and by tissue elastic properties (stiffness; DE BAERDEMAEKER 1988). In food analysis the term firmness is frequently used in a very broad sense, however, physically firmness can only be determined destructively because strength is defined as the force (stress) at which a sample breaks (VINCENT 1990). In contrast, the stiffness of a produce denotes its resistance to fully reversible deformations i.e. following Hooke's law. Hence, stiffness can be measured non-destructively by quasi-static compression tests (MOHSENIN 1986) and characterised by the apparent elastic modulus (ASAE 1999). More recently, dynamic acoustic impulse-response measurements (YAMAMOTO et al. 1980) provide the stiffness factor (*S*), which is sometimes simplifying referred to as acoustic firmness or firmness index (SHMULEVICH et al. 2003). The acoustic impulse-response method is fast and yields a produce-averaged value (CHEN 1996). DE BAERDEMAEKER (1988) compared the acoustic impulse-response to consumer acceptability of fruit and found that this technique can yield "a range of stiffness values for which there is good consumer acceptability". Furthermore, stiffness factor highly correlates with sensory firmness (ABBOTT et al. 1968; GALILI and DE BAERDEMAEKER 1996). Thus, it is a useful parameter to describe food texture.

Tissue elastic properties are interdependently determined by water status and cell wall mechanical parameters (VON WILLERT et al. 1995). Short-term texture changes under unfavourable storage conditions mainly result from a decline in cell water potential or its mechanical component, the pressure potential (or turgor), due to a decline in water volume, while physical cell wall properties may remain unchanged (HERPPICH et al. 1999a). Thus, short-term changes could be distinct from long-term changes of produce mechanical properties (HERPPICH et al. 2000) related to a variation of the chemical composition of the wall material (ZHOU et al. 1999). The latter may occur independent of water potential or water content (HERPPICH et al. 2001a) and will be referred to as softening. Consequently, NERYA et al. (2001) raised the question whether "the acoustic response of fruits" is "a measure of firmness or of turgor?" However, the answer is still missing.

The effects of water potential and turgor on produce strength and elastic properties have been investigated before (FALK et al. 1958; DE BAERDEMAEKER et al. 1978; MURASE et al. 1980a,b; LIN and PITT 1986; BAJEMA et al. 1998; DE BELIE et al. 2000). However, these studies used destructive approaches to determine water status and mechanical properties. Turgor was often estimated relatively from water volume changes of the produce immersed into solutions (e.g. mannitol) of various osmotic concentrations (LIN and PITT 1986; DE BELIE et al. 2000), a method known to introduce artificial effects (BAJEMA et al. 1998). In contrast, the combination of the pressure bomb technique and pressure-volume analysis (VON WILLERT et al. 1995) has been shown to obtain non-destructively comprehensive information about water potential, pressure potential and volumetric elastic modulus (HERPPICH et al. 1999b).

Hence, the aim of this investigation was to examine non-destructively the interactive effects of produce water status and elastic properties. An experiment was designed to test whether the above-mentioned methods (quasi-static compression test, acoustic impulse-response and pressure-volume-analysis) measure water-deficit dependent texture changes. Furthermore, it should be clarified whether the change of apparent elastic modulus and stiffness factor is directly related to those of plant water status over a wide range of water

potential or water content, respectively. In this study radish tubers were used as a model produce. They are very sensitive to transpiration-related dehydration and their water potential can easily be obtained from pressure bomb readings. Furthermore, radish tubers have a relative simple morphological and histological structure, which may increase the reliability of acoustic stiffness measurements (CHEN 1993) and quasi-static compression tests.

Materials and Methods

Bunches of fresh radishes (*Raphanus sativus* L.) were purchased at a local supermarket. Before starting the experiment, the leaves of all radishes were detached. Then the tuber fresh mass (*FM*) and water potential were obtained immediately followed by the acoustic measurement and the quasi-static compression test. Further changes in water potential, elasticity and fresh mass of 21 tubers (on four different sessions or days) were repeatedly assessed at intervals during controlled dehydration by free transpiration. Finally, the tubers were dried to constant weight in an oven (85°C), and dry mass (*DM*) was obtained afterwards.

Mean tuber water potential (Ψ) was measured with a pressure chamber (Plant Water Status Console 3000, Soilmoisture, USA) via the cut root tip (HERPPICH et al. 1999a). For the acoustic impulse-response measurements, a little hammer was used to slightly strike the radishes. The resulting sound was recorded with a microphone connected to a computer (Fig. 1). Measure-

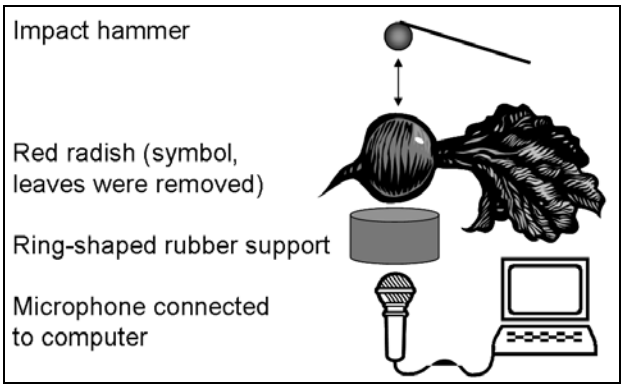


Fig. 1. Scheme to illustrate the breadboard construction for measuring the resonant frequencies of radish tubers with the acoustic impulse-response technique.

ments were repeatedly (five times per tuber) performed at the equator. The frequency at the first local maximum in the frequency spectrum was obtained after a fast Fourier transformation of the raw sound signal. An algorithm was used for analyses multiplying the single frequency spectra to eliminate unwanted local peaks. Frequencies below 230 Hz were omitted. The stiffness factor (S) was calculated from the frequency (f) and the respective tuber fresh mass as

$$(S = f^2 FM^{2/3}).$$

Tubers' apparent modulus of elasticity (E) was determined from compression tests with a universal testing machine (Zwicki 1120, Zwick, Ulm, Germany) with a spherical steel body (diameter d = 6.35 mm; compression rate =10 mm min^{-1}). A funnel-shaped holder supported the tubers. E was calculated from the deformation (D) at a force (F) of 2 N,

$$E = \frac{0.531F(1-\mu^2)}{D^{3/2}}\left[\frac{2}{R}+\frac{4}{d}\right]^{1/2}$$

(MOHSENIN 1986) where μ = Poisson's ratio = 0.49 (same as for whole potatoes, MOHSENIN 1986), R = mean radius of radishes from perpendicular diameters and length.

From the water potential/*FM* data sets, the respective water saturated tuber mass (*SM*) was determined by extrapolating these data to a water potential of zero MPa. The relative water deficits (*RWD*) were calculated as

$$RWD = 1 - \frac{FM - DM}{SM - DM}$$

Type-II pressure - volume (PV-) curves were constructed (cf. VON WILLERT et al. 1995) by plotting the inverse water potential against *RWD*, and they were used to transform the actual tuber water potential into its pressure (volume averaged pressure potential or turgor; Ψ_P) and osmotic components (HERPPICH et al. 2001a). The volume averaged volumetric modulus of elasticity (ε) was calculated from changes in pressure potential and in *FM* during two subsequent measurements multiplied by the initial *FM* (FM_i).

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

All data points from the original set were used. Regression analysis was used for the important trends of the produce properties.

Results

As long as tubers were turgescent, E declined rapidly and linearly with decreasing water potential (Fig. 2A). When tubers were wilted, E decreased only slowly with further water losses, i.e. the slope of this relationship largely flattened when water potentials below turgor loss were reached. The bending point of both the combined data sets and of most single tubers (specified in Fig. 2A on the example of two individual tubers) closely reflects the mean range of water potentials at which the average tuber turgor was lost (–0.80±0.16 MPa). In this wilting range of radish tubers the average E was 3.64±0.69 MPa. The presented data indicate that the influence of water status on the apparent elastic modulus becomes low, when there is no positive intrinsic hydrostatic pressure.

The correlation between S and Ψ was weaker than that between E and Ψ (Fig. 1B), although the general trends were similar. Especially in the wilting range a

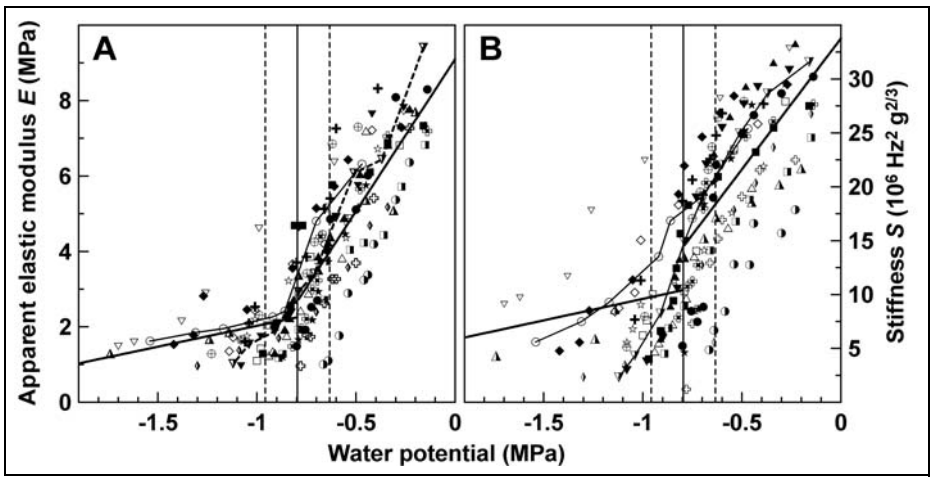


Fig. 2. Effects of water potential on (A) apparent elastic modulus E and (B) stiffness factor S. Data were obtained in parallel during the rapid dehydration (during the course of one day) of 21 radishes (each indicated by an individual symbol). Symbols connected by lines point out the respective results of two individual tubers. The vertical lines indicate the water potentials in the wilting range (solid line: mean water potential at turgor loss of all radishes, the dotted lines: ±SD).

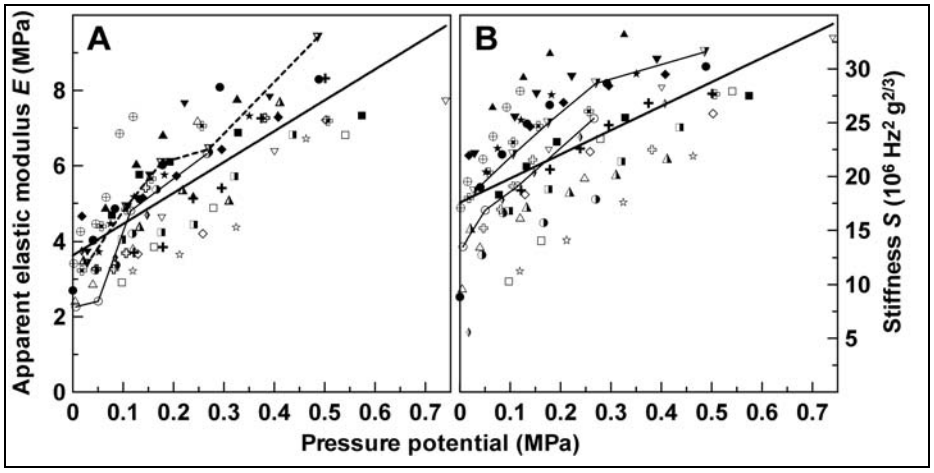


Fig. 3. Apparent elastic modulus E (A) and stiffness factor S (B) as a function of pressure potential. The pressure potential was estimated from PV-analyses of 21 radishes with the necessary fresh mass/ water potential data sets were recorded during the rapid dehydration (during the course of one day). Symbols connected by lines point out the respective results of two individual tubers.

larger variability of S was found (Fig. 2A and B). Visual inspection of Fig. 2A and B indicates that the dependence of S on Ψ differs from that of E on Ψ.

Both the apparent elastic modulus and the stiffness factor increased more or less linearly with tuber pressure potential as a plot of the data of all 21 radish tubers indicates (Fig. 3A and B). Again, the variability of S, when plotted as a function of Ψ_P, was higher than that of E, and S increase was slightly flatter, so their correlation was less pronounced. However, the almost linear relation between elasticity and turgor reflects, that the hydrostatic pressure within the parenchymatous tissue of a fresh perishable produce determines its elastic properties not exclusively but to a great extend.

Plant tissue generally tends to become more deformable as its water content declines. Hence, a plot of the elasticity data against the respective relative water deficits revealed a very close correlation between E and RWD, and S and RWD, respectively (Fig. 4A and B). However, while the data set of E and RWD could be best fitted using a simple power model the stiffness factor decreased exponentially with increasing RWD. The average RWD at zero turgor of all 21 radish tubers was found to be 0.11±0.08 (standard deviation, SD).

The volumetric elastic modulus is a direct measure of the cell wall stretching effect of the intrinsic hydrostatic tissue pressure (i.e. turgor) on its elastic properties (c.f. VON WILLERT et al. 1995). Based on definition, it becomes zero with turgor loss. The volumetric elastic modulus increases linearly with pressure potential (Fig. 5A). However, the decline of ε with increasing RWD is best described by a power model (Fig. 5B).

Despite E and S not being equally related to RWD, they showed a very similar dependence when plotted as a function of the volumetric elastic modulus ε (Fig. 6A, B). Both E and S obviously reach a more or less constant value at very high ε. This may indicate that the resistance of cell walls and overall tissue against the stretching force exerted by the intrinsic hydrostatic pressure effectively prevents further increase in water volume by increasing the stiffness of the cell walls. This, however, cannot be detected by applying an external force, i.e. the changes in E and S were almost constant in the pressure potential range (Fig. 33). In contrast, ε tended to further increase in the very high turgor region (Fig. 5A).

The presented data revealed difference in the dependence of E and S on water potential and pressure potential, and water content as well. Hence, it is not surprising that these parameters are not linearly correlated (Fig. 7). In contrast, there seems to be a logarithmic relationship between E and S. In turgescent tubers, the relative changes in the stiffness factor were smaller than those of the apparent modulus.

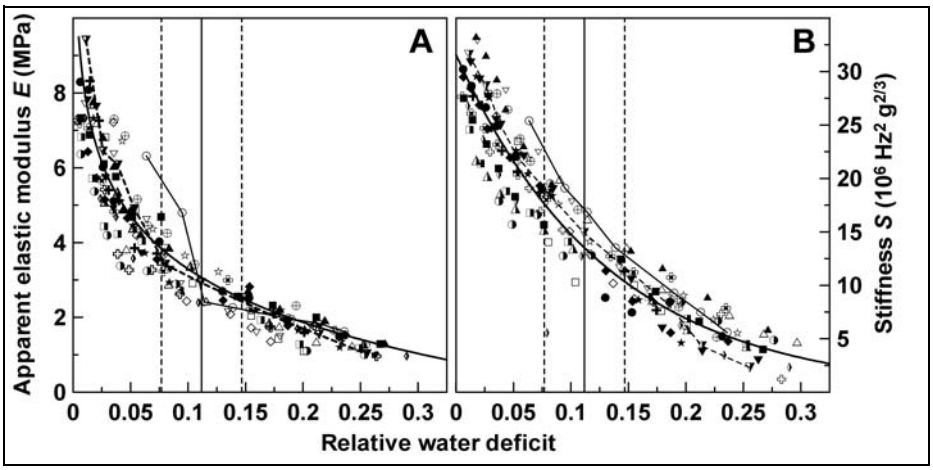


Fig. 4. Variation of the apparent elastic modulus E (A) and the stiffness factor S (B) with increasing relative water deficits. Data of 21 individual intact radishes were collected during successive desiccation by free transpiration. Symbols connected by lines point out the respective results of two individual tubers.

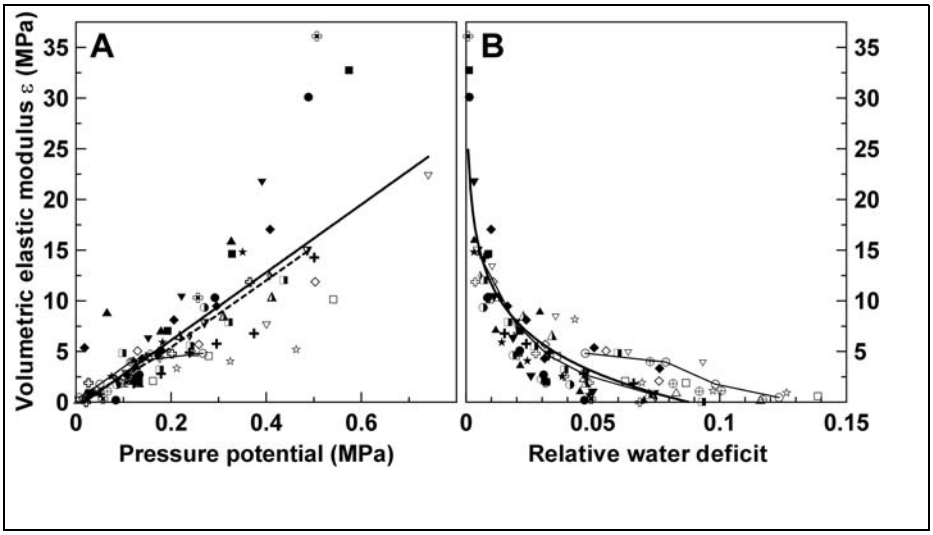


Fig. 5. Volumetric elastic modulus ε as a function of pressure potential (A) and relative water deficits (B), respectively. Data of all parameter were derived from PV-analyses of 21 radishes. The volumetric elastic modulus was calculated from changes in pressure potential and fresh mass as indicated in the Materials and methods section. Symbols connected by lines point out the respective results of two individual tubers.

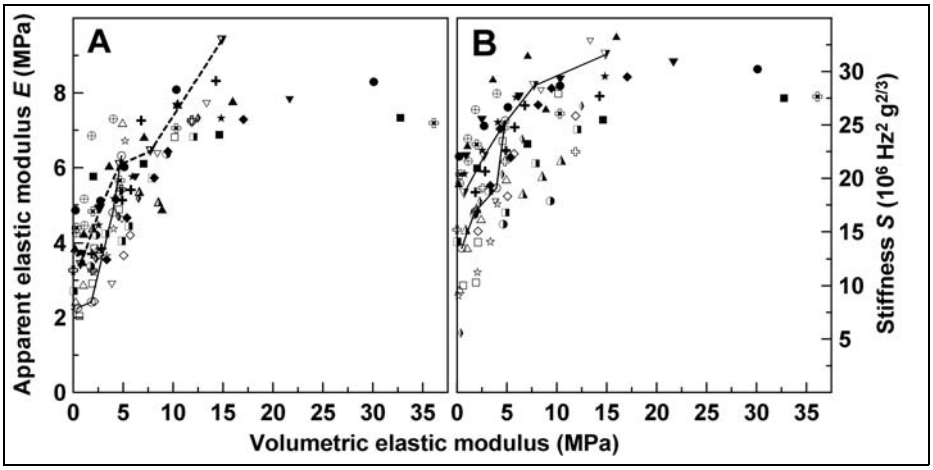


Fig. 6. Apparent elastic modulus E (A) and stiffness factor S (B) plotted against the volumetric elastic modulus as calculated from variation of tissue water content and volume averaged pressure potential by means of PV-analysis. Symbols connected by lines point out the respective results of two individual tubers.

Discussion

The elastic properties of fresh fruit and vegetables are, in a very complex and produce specific manner, interdependently determined by their morphological and histological structure, the chemical and physical properties of their cell walls, the water potential of the produce and its mechanical component, the pressure potential, and the symplastic water volume (HARKER et al. 1997; DE BELIE et al. 2000; HERPPICH et al. 2001b). The morphological aspects certainly entail a species-specific variation in the elastic properties of produces, and their overall mechanical properties as well. However, postharvest changes in produce elasticity are restricted to either maturation- and/or senescence-related alteration of the cell walls' chemistry or to changes in water status.

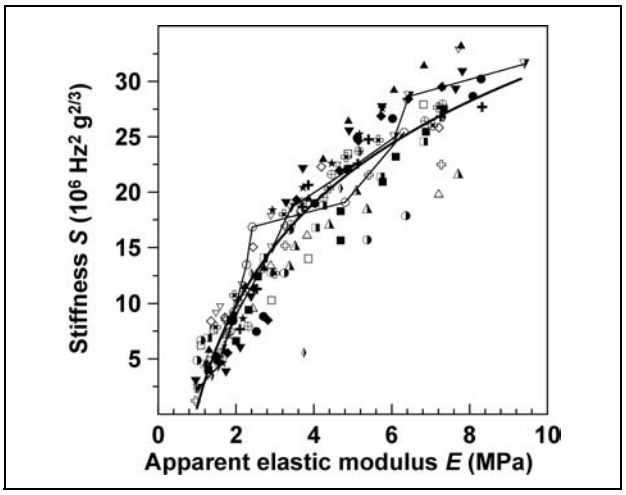


Fig. 7. Interrelationship between the apparent elastic modulus E and the stiffness factor S as measured by means of the acoustic impulse-response technique. Both E and S were repeatedly measured parallely on 21 radishes (indicated by individual symbols) while tubers rapidly lost water by free transpiration.

Under the unfavourable environmental conditions often occurring in retail, high water deficits can rapidly develop in perishable fresh products such as radishes or carrots (HERPPICH et al. 1999a, b, 2001a). The presented results imply, that the decline in water content and water potential due to increasing water losses ultimately result in a soft, low-quality produce. The softening is not expected to be caused by changes in the cell walls, since it has been shown, that cell wall mechanical properties do either not change during rapid dehydration or, if so, may even stabilize texture due to a drought induced elastic adjustment (HERPPICH et al. 2000).

The bending point observed in the relation of E and S on water potential closely reflects the mean water potential at which the average tuber turgor was lost. This indicates that the influence of water status on tissue mechanical properties becomes nearly negligible when there is no positive intrinsic hydrostatic pressure, i.e. when pressure potential is zero (HERPPICH et al. 2001a). Beyond the wilting point E decreased very slowly with further water losses. At the wilting point of radishes E was between 1.2 and 4.6 MPa. In contrast, in carrots the elastic modulus at the wilting point was found to be approx. 8 MPa (HERPPICH et al. 2001a). This indicates a much lower contribution of the thin cell walls and relatively simple tissue structure on elastic properties in radish if compared to carrots.

Hence, the initial large variations in tissue elastic properties with decreasing water potential reflect the decline in hydrostatic pressure due to the decrease in pressure potential. Thus, the results obtained from intact entire products and elaborated with non-destructive methods verified earlier conclusions from studies using destructive and indirect methods (FALK et al. 1958; MURASE et al. 1980b; LIN and PITT 1986).

The above conclusions are valid independent of whether stiffness was measured quasi-statically or dynamically (FALK et al. 1958). Nevertheless, despite the fact that the E-measurement is affected by local conditions at the contact point in that it was obtained on the radishes, E seem to have a stronger relation to the volume averaged produce's water status than the produce averaged stiffness factor. The measurements of S are largely affected by overall body conditions. Hence, gradients of water status, potentially occurring within tubers (LIPPERT 2000) may not be relevant for the relation between E and Ψ_P during natural dehydration, but might impair the validity of S as a measure of turgor-related produce changes. From this it follows, that E seems to be a more robust indicator of short-term water status-related changes in tissue elastic properties.

Furthermore, it has been shown that it becomes more difficult to obtain reliable data with the acoustic technique when the examined product becomes very soft (DE KETELAERE and DE BAERDEMAEKER 2001). The determination of the resonant frequency appears to be less accurate with increasing heterogeneity, deviating sphere-shape and increasing damping (decreasing vibration time). This could have led to the scattered stiffness at low water potential of the radishes. On the other hand, this cannot explain the worse correlation of S (compared to E) and ε. The volumetric elastic modulus is a direct measure of the cell wall stretching effect of the intrinsic hydrostatic tissue pressure (i.e. turgor) on tissue elastic properties (c.f. VON WILLERT et al. 1995). It is known as a valuable indicator of the elastic properties of the entire tissue.

Hence, it may be concluded that S is not a true indicator of mean tuber elastic properties. However, this contradicts published data denoting the ability of the acoustic impulse-response techniques to follow changes of mechanical properties in many different products (CHEN 1993; SCHOTTE et al. 1999; TU et al. 2000; LANDAHL et al. 2000). Most of these studies investigated the long-term variation in fruit texture during maturation or storage, which were mostly due to changes in the cell wall structure, and, only to a minor degree due to direct short-termed water status effects. Although TU et al. (2000) found that S of apples declined significantly faster during simulated shelf storage at low (rH=30 %) than at high air humidity (rH=95 %), their experiments lasted more than 20 d. During this time and at the temperature used (T=20 °C), changes in cell wall properties are highly probable. Thus, S is an indicator of mean tuber elastic properties, but to a much lesser extent of those that are short-term water-status-related.

In conclusion, for the first time non-destructive instrumental techniques were used to examine the interdependence of a large variety of parameters of produce quality during rapid desiccation. The water potential directly measured on the fruit level gives valuable information on the interrelation between elastic property and internal water status of the produce. The physical and the physiological parameters are closely linked. It becomes apparent that E has a stronger relation to the produce's water potential than S, which itself is a valuable indicator for the water content change in the produce. Nevertheless, both described techniques are basically able to illustrate texture changes that are due to water loss. S and E are highly correlated. However, E expresses a more pronounced dependence on short-term water potential changes in this study. Hence, S is less related to short-term changes of product rigidity than E. A combination of both properties

may therefore be a more appropriate indication of the produce condition. In the future, it remains to be examined if *S* is a sensitive parameter beyond the turgor-loss-region. It will be investigated how much the dynamic stiffness depends on cell wall properties and tissue composition or structure. Nevertheless, the acoustic response of fruits is certainly not "a measure…..of turgor" (NERYA et al. 2001).

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References

ABBOTT, J.A., G.S. BACHMAN, R.F. CHILDERS, J.V. FITZGERALD and F.J. MATUSIK 1968: Sonic technique for measuring texture of fruits and vegetables. Food Technol. **22**, 635–646.

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

BAJEMA, RW, G.M. HYDE and A.L. BARITELLE 1998: Effects of mannitol on turgor and on failure stress and strain in potato tissue. Postharvest Biol. Technol. **14**, 199–205.

CHEN, H. 1993: Analysis on the acoustic impulse resonance of apples for non-destructive estimation of fruit quality. Ph.D. thesis, K.U. Leuven, Belgium.

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, pp. 171–204.

DE BAERDEMAEKER, J. 1988: The use of mechanical resonance measurements to determine fruit texture. Acta Hort. **258**, 331–339.

DE BAERDEMAEKER, J., L.J. SEGERLIND, H. MURASE and G.E. MERVA 1978: Water potential effect on tensile and compressive stresses of apple and potato tissue. ASAE paper 78–3057. St. Joseph, Michigan.

DE BELIE, N., J.C. HALLETT, F.R. HARKER and J. DE BAERDEMAEKER 2000: Influence of ripening and turgor on the tensile properties of pear fruit: a microscopic study of cellular and tissue changes. J. Amer. Soc. Hort. Sci. **125**, 350–356.

DE KETELAERE, B. and J. DE BAERDEMAEKER 2001: Advances in Spectral Analysis of Vibrations for Non-destructive Determination of Tomato Firmness. J. Agric. Engng Res. **78** (2), 177–185.

FALK, S., H. HERTZ and H. VIRGIN 1958: On the relationship between turgor pressure and tissue rigidity. I. Experiments on resonance frequency and tissue rigidity. Physiol. Plant. **11**, 802–817.

GALILI, N. and J. DE BAERDEMAEKER 1996: Performance of acoustic test methods for quality evolution of agricultural products. Proceedings of the ISMA21-International Conference on Noise and vibration Engineering (Vol. 3), Leuven, Belgium, September18–20, pp. 1959–1972.

HARKER, F.R., G.H. STEC, I.C. HALLET and C.L. BENNETT 1997: Texture of parenchymatous plant tissue: a comparison between tensile and other instrumental and sensory measurements of tissue strength and juicines. Postharvest Biol. Technol. **11**, 63–72.

HERPPICH, W.B., H. MEMPEL and M. GEYER 1999a: Effects of postharvest mechanical and climatic stress on carrot tissue water relations. Postharvest Biol. Technol. **16**, 43–49.

HERPPICH, W.B., H. MEMPEL and M. GEYER 1999b: Water potential, an easy to measure and sensitive indicator of mechanical and climatic stress during postharvest handling of carrots. In: HÄGG, M., R. AHVENAINEN, A.M. EVERS and K. TIILIKKALA (eds), Agri-Food Quality II. Quality Management of Fruits and Vegetables. Royal Society of Chemistry, Cambridge, 256–260.

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

HERPPICH, W.B., M. LINKE, S. LANDAHL, and A. GZIK 2001b: Preharvest and postharvest responses of radish to reduced water supply during growth. Acta Hort. **553**, 89–90.

LANDAHL, S., N. De BELIE, J. DE BAERDEMAEKER, A. PEIRS and B.M. NICOLAÏ 2000: Non-destructive and destructive firmness measurements on apples and peaches. IFAC Conference on Modelling and Control in Agriculture, Horticulture and Post-Harvest Processing. July 10-12. Wageningen, The Netherlands, 6 pp.

LIN, T.-T. and R.E. PITT 1986: Rheology of apple and potato tissue as affected by cell turgor pressure. J. Texture Studies **17**, 291–313.

LIPPERT, F. 2000: Hydrophysikalische Gewebeeigenschaften von Kohlrabiknollen (*Brassica oleracea* var. *gongylodes* L.). Gartenbauwissenschaft **65**, 102–106.

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

MURASE, H., G.E. MERVA, L.J. SEGERLIND and J. DE BAERDEMAEKER 1980a: Importance of the water potential concept in studying physical properties of plant materials. 2nd International conference on physical properties of agricultural materials, Gödöllö, 8 pp.

MURASE, H., G.E. MERVA and L.J. SEGERLIND 1980b: Variation of Young's modulus of potato as a function of water potential. Transactions of the ASAE **23**(3), 794–796, 800.

NERYA, O., T. BEN-SHIMOL, A. GIZIS, A. ZVILLING, A. SHARABI-NOV and R. BEN-ARIE 2001: Is the acoustic response of fruits a measure of firmness or of turgor? Acta Hort. **55**, 473–475.

ROSENTHAL, A.J. 1999: Relation between instrumental and sensory measures of food texture. In: ROSENTHAL A.J. (ed.) Food texture: measurement and perception. Aspen Publishers, Inc., Maryland, pp 1–4.

SHMULEVICH, I., N. GALILI and M.S. HOWARTH 2003: Nondestructive dynamic testing of apples for firm-

ness evaluation. Postharvest Biol. Technol. **29**, 287–299.

SCHOTTE, S., N. DE BELIE and J. DE BAERDEMAKER 1999: Acoustic impulse-response technique for evaluation and modelling of firmness of tomato fruit. Postharvest Biol. Technol. **17**, 105–115.

TONG, T., D. KRUEGER, Z. VICKERS, D. BEDFORD, J. LUBY, A. EL-SHIEKH, K. SHACKEL and H. AHMADI 1999: Comparison of softening-related changes during storage of 'Honeycrisp' apple, its parents, and 'Delicious'. J. Amer. Soc. Hort. Sci. **124**, 407–415.

TU, K. 1998: Destructive, non-destructive and analytical measurements to determine post-harvest quality of fruits. Ph.D. thesis, K.U. Leuven, Belgium.

TU, K., B. NICOLAÏ and J. DE BAERDEMAEKER 2000: Effects of relative humidity on apple quality under simulated shelf temperature storage. Sci. Hort. **85**, 217–229.

VINCENT, J.F.V. 1990: Fracture properties of plants. Adv. Bot. Res. **17**, 235–287.

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

YAMAMOTO, H., M. IWAMOTO and S. HAGINUMA 1980: Acoustic impulse-response method for measuring frequency of intact fruits and preliminary applications to internal quality evaluation of apples and watermelons. J. Texture Studies **11**, 117–136.

ZHOU, H.-W., R. BEN-ARIE and S. LURIE 1999: Analysis of cell wall components in juice of 'Flavortop' nectarines during normal ripening and woolliness development. J. Am. Soc. Hort. Sci. **124**, 424–429.

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