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Grape berry splitting and some mechanical properties of the skin

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Das Platzen von Weinbeeren und einige mechanische Eigenschaften der Beerenhaut

Zusammenfassung: Zur Messung von mechanischen Eigenschaften der Haut reifender Weinbeeren wurden Methoden entwickelt, bei denen definierte Wassermengen über feine, durch die Beerenstielchen eingeführte Injektionsnadeln in die Beeren injiziert wurden. Die Injektionen erhöhten den Turgor der Beeren; nach Erreichen eines Fließstillstands in der Nadel wurde dieser gemessen. Im Bereich niedriger Drücke war die Ausdehnung der Beerenhaut elastisch, bei höheren Drücken war sie plastisch, wobei irreversible Veränderungen der Beerenhaut erkennbar wurden. Bei sehr hohen Drücken platzten die Beeren in einer Weise, wie sie auch im Freiland zu beobachten ist. Messungen an Beeren von 9 Rebsorten bei konstanter Temperatur (15 °C) ergaben Unterschiede im Elastizitätsmodul (1700—5400 N m^{-1}), in der Platzspannung (110—420 N m^{-1}) und bei der linearen Ausdehnungsmeßzahl (0,027—0,112). Wie bei den meisten Materialien nahm die Starrheit und Härte der Beeren mit steigender Temperatur ab (10, 30, 50 °C). Veränderungen der Beerentemperatur verursachten Veränderungen im Druck (0,44 ± 0,1 kPa °C^{-1}). Höhere Temperaturen und Drücke (50 °C, 40 kPa) hatten dauerhafte, plastische Deformationen zur Folge. Es kann angenommen werden, daß die sortenspezifische Neigung zum Platzen der Beeren mit den mechanischen Eigenschaften der Beerenhaut zu erklären ist.

Key words: berry, skin, physical properties, elasticity, splitting, analysis, apparatus, pressure, temperature, variety of vine.

Introduction

Berry splitting leads to significant commercial losses in table and wine grape production by reducing both quality and yield (CONSIDINE 1973; WINKLER *et al.* 1974). The problem of fruit splitting has been approached from a number of different perspectives. For example, studies have been made of the environmental factors involved. In particular these include aspects of the weather and the availability of soil water (BERNSTEIN and LUSTIG 1984). On the other hand a significant genetic contribution is indicated by the distinct differences in susceptability which occur between varieties.

In physiological terms, splitting which occurs at the stage of ripening can be attributed to excessive rates of volume growth resulting from large imbalances between the fluid flows to and from fruit (LANG 1988). From the results of CONSIDINE and KRIEDEMANN (1972), BERNSTEIN and LUSTIG (1984) and LUSTIG and BERNSTEIN (1985) it is evident that the skin of grape berries is elastic to some degree. Within limits the berries are able to buffer some excess of water inflow/outflow thereby avoiding splitting. The buffering capacity of the skin is developed in stage III of berry development which is characterized by rapid volume increase with cell expansion and sugar and water uptake and also by an increase in the softness or deformability of the berry (COOMBE 1976; COOMBE and BISHOP 1980).

This perspective raises questions not only of the mechanisms by which the various factors influence a berry's fluid balance but also of how they influence the extensibility of the skin. In the present study we examine a number of mechanical properties of the skin which determine its extensibility with special reference to their temperature dependences.

Materials and methods

Clusters were collected from vineyards or glasshouses at the Bundesforschungsanstalt für Rebenzüchtung Geilweilerhof, Siebeldingen (BRD), at the DSIR/MAFTech Research Centre at Te Kauwhata (NZ) and from commercial glasshouse at Mangere (NZ). The berries had all entered the ripening stage (15—20 °Brix) when measurements were made.

For each experimental run a berry without apparent blemishes was cut from the cluster with about 8 mm of pedicel still attached. Hydraulic contact with the fluid in the vicinity of the seeds was established by inserting a 27 gauge dental hypodermic needle through the pedicel base (so as not to damage the skin of the berry). Distilled water was injected and the berry's internal pressure monitored directly (Fig. 1). The following set up procedure prevented leakage around the needle and achieved good hydraulic communication with the berry, i.e., debris did not block the needle. The pedicel end of the berry was held above a concentrated ammonia solution for a few seconds to neu-

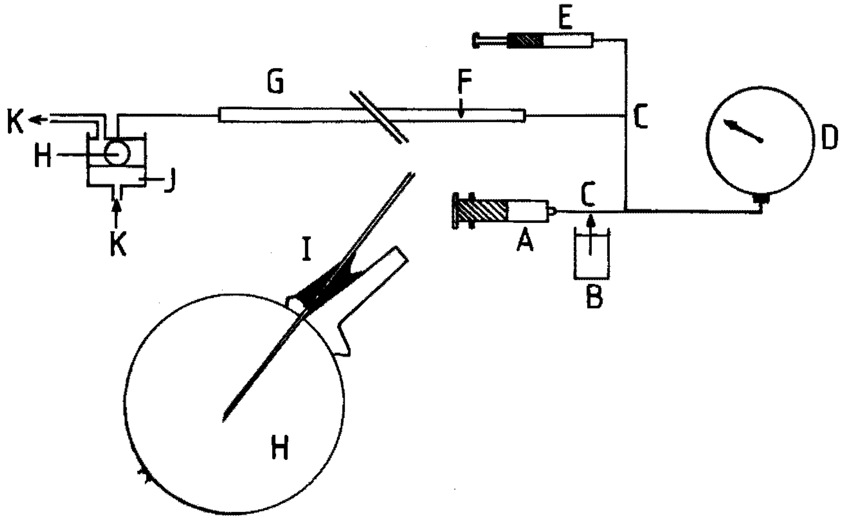

Fig. 1: Diagram of experimental set up showing: A = 20 ml ground glass syringe, B = small reservoir of distilled water used to refill A, C = 3-way taps, D = pressure gauge 0—140 kPa, E = 1 ml disposable plastic syringe for introducing of F = an air bubble ($\simeq$ 50 µl) to the capillary, G = 1.13 mm ID ($\simeq$ 1 µl mm^{-1}) precision glass capillary 1 m long, H = a berry with a 27 g gauge dental hypodermic needle inserted and sealed with I = cyanoacrylate adhesive, J = glass cuvette partly filled with glass beads to distribute the K = thermoregulated water flow.

Darstellung der Versuchsanordnung: A = 20 ml Glasspritze, B = kleiner Vorrat an destilliertem Wasser, um A zu füllen, C = Dreiwegehähne, D = Manometer 0—140 kPa, E = 1 ml Kunststoffspritze zur Einbringung einer F = Luftblase ($\simeq$ 50 µl) in die Kapillare, G = Präzisionsglaskapillare, 1 m lang, 1,13 mm innerer ∅ ($\simeq$ 1 µl · mm^{-1}), H = eine Beere mit einer eingeführten und abgedichteten 27 g (Norm-) Dentalinjektionsnadel, I = Cyanakryl-Kleber, J = Glasküvette, teilweise mit Glaskugeln gefüllt, zur Umverteilung des K = temperaturgeregelten Wasserflusses.

tralise any acid radicals which otherwise might impair the bond with cyanoacrylate adhesive used later to seal around the needle. Then a pilot hole was made prior to inserting the needle connected to the measuring apparatus (see Fig. 1). A drop of cyanoacrylate adhesive was then applied and run carefully around the union to form a good seal, and set rapidly, using Loktite 711® (post assembly activator). The pressure gauge and capillary (1.13 mm ID and therefore about 1 µl mm^{-1}) were previously calibrated. The water pressure in the apparatus was finely adjustable using a precision ground glass syringe (20 ml) mounted on a screw drive device.

Skin properties were measured by inflating berries in increments of about 25 µl. Each time the pressures were carefully balanced in the berry and in the apparatus by adjustment of the syringe drive so as to null the movement of the air bubble in the capillary. When this was achieved, pressure and incremental volume were recorded. This procedure was repeated until the berry finally split. Each incremental injection and pair of measurements took around to 1—1.5 min to complete and the total volume injected before splitting was of the order of 300—500 µl. This meant that a berry was inflated gradually over a period of about 20—25 min and the skin properties inferred from these measurements relate therefore to this rate of change of stress.

Berry temperature was controlled by immersion in water in a glass cuvette through which water from a thermoregulated bath was passed. Temperatures in the range of 10—50 °C were chosen for the experiments since these represent the approximate range of temperatures to which a grape berry might be subjected under field conditions (SMART and SINCLAIR 1976). Separate experiments confirmed that over the time scale of these measurements insignificant water exchange took place between cuvette and berry.

Skin properties for rapidly changing temperatures were measured by inflating a berry as described above to a pressure somewhere in the middle of its elastic range, then rapidly changing its temperature by switching the source of water being circulated through the berry cuvette from one thermoregulated water bath to another. Three bath temperatures were used in these measurements: 10, 30 and 50 °C. Temperature change in the cuvette was found to be substantially complete in 15 s and in the berry within 1.5 min (SMART and SINCLAIR (1976) reported a time constant for temperature change in grapes of this order).

As berry temperature changed, pressure in the apparatus was continuously adjusted so as to match the changing pressure in the berry, the balance being monitored by nulling the movement of the air bubble in the capillary as before. This meant that no exchange of fluid between the berry and the apparatus took place after the initial partial inflation.

The coefficient of thermal expansion of the berry contents was measured in a separate experiment in which centrifuged sap was introduced to a small glass dilatometer. Any gaseous air contained in the berry would necessitate a correction for its compressibility in subsequent calculations. Therefore, the presence of air was checked for by destroying berries by crushing them under an inverted water filled beaker. No air was found.

Results and discussion

The general pattern of results is illustrated (Figs. 2—5) using data obtained with the variety Portugieser. Results for Portugieser and the other varieties are presented in summary form only in the following table.

Values of elastic modulus (Et_{15}), bursting tension (T_{15}^*) and linear bursting strain (S_{15}^*) at 15 °C for 9 grape varieties · The temperature coefficients of these parameters (see text for explanation) are α, β and γ respectively

Werte des Elastizitätsmoduls (Et_{15}), der Platzspannung (T_{15}^*) und der linearen Ausdehnungsmeßzahl (S_{15}^*) bei 15 °C für 9 Rebsorten · Die Temperaturkoeffizienten dieser Parameter (Erklärungen im Text) sind α, β und γ

Varieties	Et_{15} (Nm^{-1})	α (°C^{-1})	T_{15}^* (Nm^{-1})	β (°C^{-1})	S_{15}^* (—)	γ (°C^{-1})
Portugieser	1700	N.S.	270	0.006	0.112	N.S.
Sultana	3100	−0.015	160	0.007	0.043	0.0123
Italia	—	—	240	0.010	0.027	N.S.
Gros Coleman	1900	0.013	110	N.S.	0.045	−0.0077
Cardinal	—	—	210	0.009	0.028	N.S.
Cabernet Sauvignon	1700	0.012	130	0.007	0.068	N.S.
Black Alicante	4800	0.011	240	0.004	0.048	N.S.
Bien Donne	3400	N.S.	200	0.008	0.051	N.S.
Albany Surprise	5400	N.S.	420	0.005	0.071	N.S.

Note: — indicates that data were not available (see text). The presence of a temperature coefficient indicates a temperature dependence significant at P = 0.05 or better; N.S. indicates no significant temperature dependence.

Stress:strain relationships

The relationship between injected volume (V) and berry pressure (P) is shown for a typical Portugieser berry in Fig. 2. The resting pressure P_1 in the berry in this case was 34 kPa. The P : V relationship is more or less linear indicating elastic behaviour over most of the range. At higher values of P slight flattening of the P : V curve evidences some plastic stretch. The slope ($\Delta P/\Delta V$) of the initial part of the curve was found by linear regression and from this the longitudinal elastic modulus of the skin (E) was calculated according to the relationship

$$Et = \frac{\Delta P}{\Delta V} 2\pi r^4 (1 - \mu) \tag{1}$$

where t is the skin thickness, r is the berry radius and μ Poisson's ratio, which is taken to be 0.35. The value Et (with dimensions of surface tension) was adopted rather than E because skin thickness (around 20 µm) is ill defined. (Although the outer cuticular boundary is obvious, the inner cellular one is not.)

The modulus was evaluated at different temperatures (Fig. 3) so that its temperature dependence could be found. Temperature dependence of elastic modulus is usually expressed in the form

$$Et_\tau = Et_{15} [1 - \alpha(\tau - 15)] \tag{2}$$

where τ is temperature in °C, Et_{15} the elastic modulus at 15 °C and α the temperature coefficient of the elastic modulus. Values found for Et_{15} and for α in the 9 varieties examined appear in the table. Values of Et for the varieties Italia and Cardinal are omitted because the inflation profile was non-linear from the outset indicating some plasticity. This character may be significant in relation to splitting since both are particularly sensitive. Values for α of organic polymers lie in a similar range, which is about an order of magnitude greater than those for metals. Note from the table that the temperature coefficient for Et(α) is normally positive. In line with most materials this indicates increased stiffness at lower temperatures. The coefficient for Sultana is however negative ($P = 0.05$). This indicates a slightly unusual decreased stiffness at lower temperatures.

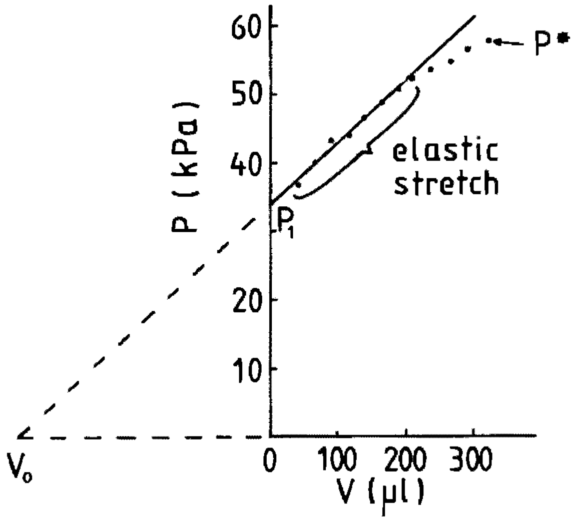

Fig. 2: The relationship of P to V for typical Portugieser berry. P_1 is resting pressure and P^* the bursting pressure. V_0 is an estimate of berry volume at zero pressure. Note the slight plastic departure just before splitting.

Die Beziehung zwischen Druck (P) und Volumen (V) bei einer typischen Portugieserbeere. P_1 ist der Ausgangsdruck und P^* der Platzdruck. V_0 ist das bei Druck = 0 angenommene Beerenvolumen. Man beachte die geringfügige Abweichung von der Geraden kurz vor dem Platzen (Bereich plastischer Veränderungen).

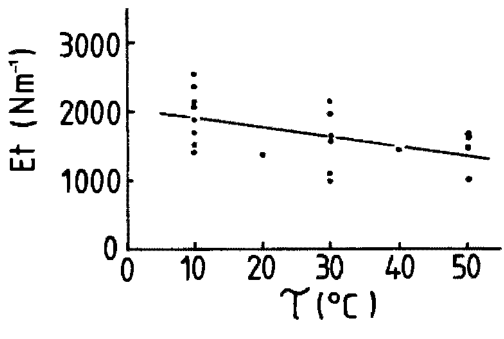

Fig. 3: The relationship between Et (elastic modulus × skin thickness) of a Portugieser berry and temperature. Note the decrease in stiffness as temperature rises. (Significant at $P = 0.05$).

Die Beziehung zwischen Et (Elastizitätsmodul × Hautdurchmesser) und Temperatur bei einer Portugieserbeere. Man beachte die Abnahme der Starrheit bei steigender Temperatur (signifikant bei P = 0,05).

It was also of interest to note that the bursting pressure, indicated by P^* in Fig. 2, was temperature dependent. Since however the stress (σ) in a thin-walled sphere is related to its radius, where

$$\sigma = \frac{Pr}{2t}, \tag{3}$$

it is more appropriate to assess the temperature dependence of the bursting stress (σ^*). Again, because of the ill-defined skin thickness we have evaluated T^* the bursting tension (where $T^* = \sigma^* t$). For most varieties this too was found to be temperature dependent (see Fig. 4 and Table). Temperature dependence may be expressed in the same form as equation (2):

$$T_\tau^* = T_{15}^* \left[1 - \beta(\tau - 15)\right] \tag{4}$$

In all varieties but one, β is significant and positive indicating increased strength at lower temperatures. This is to be expected and is in line with most other materials.

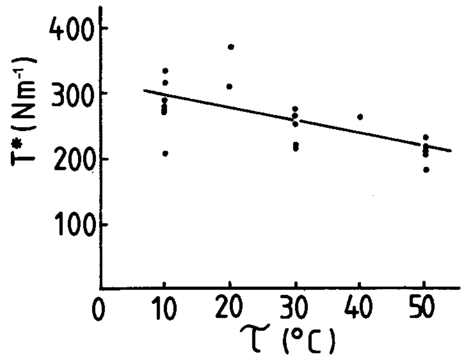

Fig. 4: The relationship between bursting tension T^* and temperature of a Portugieser berry. Note the decrease in strength as temperature rises. (Significant at $P = 0.05$.)

Die Beziehung zwischen der Platzspannung T^* und der Temperatur bei einer Portugieserbeere. Man beachte die Abnahme der Härte bei steigender Temperatur (signifikant bei $P = 0{,}05$).

The volume increase which can be sustained without rupture is also an interesting property since this measures the volume buffering capacity of the skin, during periods when fluid inflows exceed fluid outflows. Linear strain (extensibility) at bursting S^* is given by the relationship

$$S^* \simeq \frac{V^* - V_0}{3\,V_0} \tag{5}$$

where V_0 is the berry volume at zero pressure (estimated by linear extrapolation from the inflation curve) and V^* is the berry volume at bursting. For the small fractional volume changes found here the divisor 3 represents an acceptable approximation to convert from a fractional volume to a fractional linear change. Temperature dependence of S^* is expressed in the same form as equations (2) and (4):

$$S_\tau^* = S_{15}^* \left[1 - \gamma(\tau - 15)\right] \tag{6}$$

In most varieties S* was not significantly influenced by temperature (see Table.) The exceptions were Sultana in which bursting strain significantly greater at lower temperatures ($P = 0.001$) and Gros Coleman in which they were reduced at lower temperatures ($P = 0.001$). Note that the varieties with the least extensible skin (Italia and Cardinal) ($S_{15}^* \simeq 0.03$) are very sensitive to splitting.

The magnitude and general pattern of change with temperature in the major mechanical parameters of grape skin (Table) are those to be expected of organic polymer materials. The few exceptions, which have been noted, and varietal differences in the values found, may perhaps be related to the growth characteristics of each variety and to their splitting sensitivities.

Pressure:temperature relationships

The effect of temperature upon berry pressure is shown in Fig. 5. It was found that the correlation between the change in pressure and the change in temperature was highly significant being 0.44 ± 0.1 kPa °C^{-1}. The magnitude of this effect did not vary significantly with the range over which temperature changed (i.e., between 10 and 30 °C, or between 30 and 50 °C) or with the direction of temperature change (i.e., increasing or decreasing temperature). Note in the particular set of results presented in Fig. 5 that the temperature rise of 30 to 50 °C elicits a slightly reduced pressure rise per degree C. This effect was not evident for all berries. The reduction in this case may be explained as being due to some plastic deformation at the higher pressures and temperatures rather than to a smaller effect of temperature upon volume. This interpretation is supported by the observation that the pressure falls associated with the subsequent 50 to 30 °C temperature drop was of normal magnitude while the final 30 °C pressure was significantly less than the earlier ones.

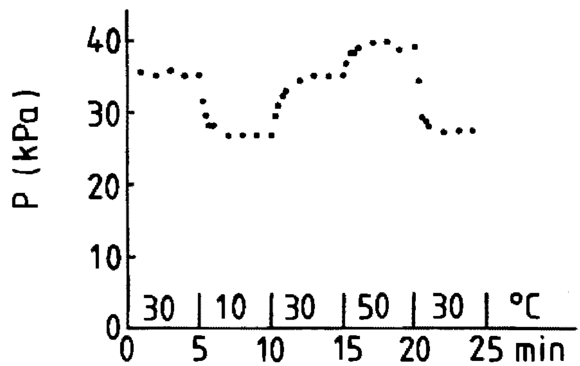

Fig. 5: The time course for changes in berry turgor with abrupt changes in temperature for a typical Portugieser berry. Note that the higher temperature and pressure (50 °C and 40 kPa) cause permanent plastic deformation, so reducing the pressure recorded for this and for the subsequent measurement.

Der zeitliche Verlauf von Änderungen im Beerenturgor bei plötzlichen Veränderungen der Temperatur einer typischen Portugieserbeere. Man beachte, daß hohe Temperaturen und Drücke (50 °C und 40 kPa) plastische Deformierungen hervorrufen und auf diese Weise den in dieser und der nachfolgenden Messung registrierten Druck herabsetzen.

The strong rise in berry pressure with temperature may explain why splitting often occurs in the early part of the day as sunlight falls upon cold fruit. The dramatic effect of temperature change upon pressure was not anticipated. Some effect of changing temperature upon berry pressure is of course likely, since it is improbable that skin and contents will have identical coefficients of cubic thermal expansion. Also since the thermal expansions of fluids generally exceed those of solids, we would have predicted that pressure would rise with increasing temperature rather than fall. What was not anticipated was the magnitude of the pressure increase. Increase in sap volume with temperature is given by

$$\Delta V = \gamma_{sap} V \Delta T \tag{7}$$

where ΔV and ΔT are the changes in volume and temperature of a volume of sap V and γ the coefficient of cubic expansion. The coefficient of cubic expansion of centrifuged grape contents compared very closely with published values for sugar solutions of similar concentration. We recorded a value for γ_{sap} of $328 \times 10^{-6}\,°C^{-1}$ over the range 10—50 °C. This, for a 17 mm diameter berry rising in temperature from 10 to 50 °C corresponds to the volume increase of only 34 µl. The pressure : volume relationship (Fig. 2) indicates that a 34 µl volume increase would cause only a 3 kPa pressure increase — not the 17 kPa increase consistently produced for this rise in temperature (Fig. 5). The strong rise in pressure with temperature is interesting, for it implies a negative value for the area coefficient of thermal expansion of the skin, i.e., that skin area reduces with rising temperature. Negative values of thermal expansivity for isotropic materials are unusual but not unknown (e.g., for water between 0 and 4 °C). Anisotropic materials on the other hand commonly have different expansivities in different directions and occasionally have negative ones in one or more directions (and correspondingly large positive ones in another direction). Our evidence for negative thermal expansivity in the planar directions for such a highly complex and anisotropic material as the epidermal and cuticular layers of a fruit, while unexpected, is not therefore to be assumed artefactual. Because of the technical interest, quite extensive further study of the phenomenon was carried out, but satisfactory experimental methods were illusive. The results obtained were unfortunately unable either to confirm or discount the evidence presented here which was judged reasonably compelling and was, moreover, highly reproducible and consistent across several varieties.

Conclusion

Splitting resistance depends in part on the extent to which a grape can accomodate a period of rapid volume growth without damage and this depends on the mechanical properties of its skin.

Techniques have been developed through which the stiffness, strength and extensibility of grape skin can be measured as a function of temperature. Varietal differences in splitting resistance may be explainable in terms of these properties.

The strong rise in internal pressure of a grape observed with increase in temperature may cause splitting in certain circumstances. This is made more likely because at higher temperatures there is also a significant decrease in skin stiffness and strength.

Summary

Techniques were developed to measure some of the mechanical properties of the skin of grape berries in the ripening stage. These involved the injection of known quantities of water into the fruit through fine hypodermic needles inserted through their stalks. Injection gave rise to an increase in fruit turgor which was measured as the balancing hydrostatic pressure required in the needle to give no flow.

Over the lower range of pressures, skin extension was elastic, whilst at higher pressures extension was plastic with the skin suffering permanent deformation. At the highest pressures, splitting occurred of a sort similar to that observed in the field. Berries of 9 grape varieties measured at constant temperature (15 °C) differed in their elastic modulus (1700—5400 Nm^{-1}), their bursting tension (110—420 Nm^{-1}) and their linear bursting strain (0.027—0.112). As with most materials, berry stiffness and strength decreased at increasing temperatures (10, 30, 50 °C).

Changes in berry temperature caused changes in pressure (0.44 ± 0.1 kPa $°C^{-1}$). Higher temperatures and pressures (50 °C, 40 kPa) caused permanent plastic deformation. Varietal differences in splitting susceptibility may find explanation in terms of the mechanical properties of the skin.

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Literature

Bernard, A. C.; 1976: Résistance méchanique des baies de *Vitis vinifera* au *Botrytis cinerea* Pers. France Vitic. **8**, 301—307.

Bernstein, Z.; Lustig, I.; 1984: Influence des conditions climatiques et des propriétés méchaniques des pellicules sur l'éclatement des baies. Bull. O.I.V. **57**, 955—962.

— —; — —; 1985: Hydrostatic methods of measurement of firmness and turgor pressure of grape berries (*Vitis vinifera* L.). Sci. Hort. **25**, 129—136.

Considine, J. A.; 1972: Fruit splitting in grapes: determination of the critical turgor pressure. Austral. J. Agricult. Res. **23**, 17—24.

— —; 1973: A statistical study of rain damage of grapevines grown for drying in Victoria. Austral. J. Exp. Agricult. Anim. Husb. **13**, 604—611.

— —; 1981: Correlation of resistance to physical stress with fruit structure in grape. Austral. J. Bot. **29**, 475—482.

— —; 1982: Physical aspects of fruit growth: cuticular fracture and fracture patterns in relation to fruit structure in *Vitis vinifera*. J. Hort. Sci. **57**, 79—91.

— —; Williams, J. F.; Brown, K. E.; 1974: A model of studies on stress in dermal tissues of mature fruit of *Vitis vinifera*: criteria for producing fruit resistant to cracking. In: Bieleski, R. L.; Ferguson, A. R.; Cresswell, M. M. (Eds.): Mechanisms of Regulation of Plant Growth. Bull. **12**, 611—617. The Royal Society of New Zealand, Wellington.

Coombe, B. G.; 1976: The development of fleshy fruits. Ann. Rev. Plant Physiol. **27**, 507—528.

— —; Bishop, G. R.; 1980: Development of the grape berry. II. Changes in diameter and deformability during veraison. Austral. J. Agricult. Res. **31**, 499—509.

Düring, H.; Lang, A.; Oggionni, F.; 1987: Patterns of water flow in Riesling berries in relation to developmental changes in the xylem morphology. Vitis **26**, 123—131.

Lang, A.; 1988: Why do grape berries split? Proc. Intern. Conf. Viticult. Oenol. Auckland, 69—71.

— —; Thorpe, M.; 1989: Xylem, phloem and transpiration flows in grape. J. Exp. Bot. **40**, 1069—1078.

Lustig, I.; Bernstein, Z.; 1985: Determination of the mechanical properties of the grape berry skin by hydraulic measurements. Sci. Hort. **25**, 279—285.

SMART, R. E.; COOMBE, B. G.; 1983: Water relations of grapevines. In: KOZLOWSKI, T. T. (Ed.): Water Deficits and Plant Growth, Vol. **VII**, 137—196. Academic Press, New York.

— —; SINCLAIR, T. R.; 1976: Solar heating of grape berries and other spherical fruits. Agricult. Meteorol. **17**, 241—259.

SWIFT, J. G.; MAY, P.; LAWTON, E. A.; 1974: Concentric cracking of grape berries. Vitis **13**, 30—35.

WINKLER, A. J.; COOK, J. A.; KLIEWER, W. M.; LIDER, L. A.; 1974: General Viticulture. University of California Press, Berkeley, Los Angeles, London.

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