OPTICAL DETECTION OF MEALINESS IN APPLES USING LASER TDRS

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ABSTRACT

Mealiness is a textural attribute related to an internal fruit disorder that involves quality loss. It is characterised by the combination of abnormal softness of the fruit and absence of free juiciness in the mouth when eaten by the consumer. Recent research concluded with the development of precise instrumental procedure to measure a scale of mealiness based on the combination of several rheological properties and empirical magnitudes. In this line, time-domain laser reflectance spectroscopy (TDRS) is a medical technology, new in agrofood research, which is capable of obtaining physical and chemical information independently and simultaneously, and this can be of interest to characterise mealiness. Using VIS & NIR lasers as light sources, TDRS was applied in this work to Golden Delicious and Cox apples (n=90), conforming several batches of untreated samples and storage-treated (20°C & 95%RH) to promote the development of mealiness. The collected database was clustered into different groups according to their instrumental test values (Barreiro et al, 1998). The optical coefficients were used as explanatory variables when building discriminant analysis functions for mealiness, achieving a classification score above 80% of correctly identified mealy versus fresh apples.

INTRODUCTION

Nowadays, consumers' decision at purchase is affected both by external aspect and internal quality of fruits. Among the quality parameters that a consumer can find in apples, mealiness is a main issue. It has been defined as a negative attribute of sensory texture that combines the sensation of a dis-agregated tissue with the sensation of lack of juiciness. It is a consequence of a chemical process resulting in the pectin degradation in the middle lamellae (Von Mollendorf et al 1993; Gross et al 1984), and their consequences are visible with microscopic observation (De Smedt et al 1998). Mealiness is associated with late harvest and long term storage (Harker and Hallett 1992; Fisher 1943). Mealiness onset may be also accelerated by temperature treatments (Von Mollendorf et al 1992) combined with extremely high relative humidity (De Smedt 2000).

The characterisation of mealiness has been done traditionally by means of sensory panels defining sensorial descriptors. However, relations between physiology changes, texture of tissues and sensory measurements of strength and juiciness has been carried out succesfully (Harker et al 1997; Verlinden et al 1997). A recent EC Project (FAIR CT95-0302) was devoted to the comparison between sensory and instrumental measurements for mealiness assessment, mainly in apples (Barreiro et al 1998). Working on a large experiment (>1200 apples), correlations between sensory attributes (crispness and juiciness, at first bite and during chewing) and a combination of parameters acquired from the instrumental test (confined compression of probes) were modelled. Then, a redefinition of mealiness in apples and peaches in terms of rheological properties was proposed following human priorities in mealiness perception: a new instrumental mealiness scale was created, gathering loss of crispness, hardness and juiciness, which is able to characterise objectively the mealiness state of a given sample and correlates well with sensory mealiness. More studies can be found also with peaches (Ortiz et al. 1999a; Sonego et al. 1995) and tomatoes (Ahrens and Huber 1987).

Several approaches for future non-destructive methods of mealiness detection has been attempted using different techniques: NIR spectroscopy, low mass impact, acoustic impulse response and ultrasonic wave propagation through fruit tissues, and NMR (Barreiro et al. 1999). None of them on their own showed good prospective in relation to mealiness assessment. Fusion of NIR spectroscopy (focused on water distribution detection) and low mass impact response (to characterise hardness) showed to be adequate for the segregation of several mealiness stages in peaches (Ortiz et al. 1999b).

Nevertheless, the development of standing-alone non destructive techniques is still interesting (Abbott 1999), specially if they are fast and could be engineered into an automatic on-line classification system. TDRS or TRS (time-domain resolved spectroscopy or time reflectance spectroscopy) is a non conventional spectroscopic technique that has been developed for use in the field of medicine (Cubeddu et al 1994a) to characterise the optical properties of tissues, and to locate discontinuities and affected areas like tumours. Among its advantages compared to more traditional spectroscopic techniques, there is the feasibility to assess simultaneously and independently two optical parameters: the absorption of the light inside the irradiated body, and the scattering of the photons across the tissues, at each wavelength, thus generating two coefficients (μa, absorption coeff.; and $\mu's$, transport scattering coeff.). If it is assumed that they are related respectively to chemical components and to physical properties of the sample, TDRS can be applied to the quantification of chemicals and the measurement of the rheological properties (i.e. mealiness estimation) at the same time. Recently, time-domain resolved reflectance spectroscopy has been applied satisfactorily for the non-destructive evaluation of fruit internal quality (Valero et al. 2000) Using 490 apples from different varieties, links were found between the optical properties of the samples and their quality attributes obtained with standard procedures; statistical models were developed then for the quantification of several aspects of fruit quality (firmness estimation, sugar content and acidity). In the present work, the objective was to apply TDRS to the case of mealiness.

MATERIALS AND METHODS

To study the applicability of the TDRS technique to the detection of mealiness in apples, different samples were prepared:

1. Apples with “natural mealiness", in order to study if it is present in apples harvested late in the season: selected Golden Delicious apples were picked from the orchards (Zaragoza, Spain) during the last week of October'98 (late harvest), to conform two groups, the *a priori* non mealy apples and the mealy ones. From the whole harvest, 25 "fresh" and 25 "possibly mealy" were packed and sent to Milan (INFM) in November. The “a priori mealy” samples were selected on the trees from the whole harvest using two subjective criteria: external colour (mealy batch more golden than the fresher one) and tactile hardness.
2. Apples with mealiness induced in chamber storage: colleagues at the Catholic University of Leuven (Belgium) prepared along the autumn some samples from the Cox variety, harvested early in the season and stored until November'98 in specific

conditions: 20 of them were kept inside an ULO chamber (ultra low oxygen) to preserve their freshness at maximum levels; other 20 apples were kept along 16 days in an atmosphere of 95% relative humidity and 20°C, to promote the development of mealiness. Not all of them were expected to be finally mealy, as indicated by previous studies.

The use of the expression "a priori mealy" refers to the fact that, up to date, there is not a non destructive method to know if each unit of a batch of apples is really mealy until it is destroyed. The only destructive test that has been proven to be reliable characterising the mealy samples is the already mentioned (Barreiro et al 1998), that combines information from mechanical behaviour and juice released to classify the samples according to their level of instrumental mealiness.

The reference test (firmness) and TDRS measurements that were carried out on the samples can be summarised as indicated below (in chronological order).

TDRS measurements. TDRS is based on the measurement of the broadening of a short light pulse, transmitted across a turbid medium (fruit tissues). The light source is a laser beam, monochromatic then, but tuneable at several wavelengths. The light is injected in the fruit through the intact skin by means of fibre optics positioned perpendicularly to the equator of the fruit. The light flux crosses the tissues and part of it finds its way out of the sample at a particular region adjacent to the injection point. This portion of reflected light was recovered with other fibre optics placed at about 20 mm in parallel to the injection ones. The optical paths of the photons with larger probability of being recovered after suffering internal reflection, form a three-dimensional light region with a semi-toroidal shape, constructed from the incoming fibres to the recovering fibres. If an adequate theoretical model is used for the experimental analysis of data and several hypothesis are established, it is possible to calculate at the same time the absorption coefficient (μ_a) and the transport scattering coefficient (μ's) at each wavelength, with good precision. The TDRS equipment used in this work is described in detail in the following references: Cubeddu *et al.* 1994b; Cubeddu *et al.* 1999.

For this study, the absorption and transport scattering coefficients of both sides of each sample were registered at several wavelengths: far-visible (672, 750 & 818nm using diode lasers as light sources) and NIR (form 900 to 1000nm, at steps of 10nm using a tuneable laser). Notation for these variables is used as 'MA672' for μ_a coefficient at 672 nm, 'MS672' for μ'_s coefficient at 672 nm, and so on.

Confined compression test. Using a Texture Analyser TA-XT2 a maximum deformation of 2.5mm was applied at 20mm/min speed rate on cylindrical probes of 1.7 cm height and diameter. Deformation was immediately removed at the same speed rate; two repetitions were made per fruit (one per side) using the average for the subsequent analyses for this load/unload test. Cylinders were confined in a disk which had a hole of the probe size (see Figure 1). The rod employed for the compression test was 15.3 mm diameter to avoid any contact with the disk during testing. A filter paper (Albet nº 1305 of 77.84 gr/m^2) about the size of the disk was placed beneath the disk in order to recover the juice extracted during the compression test. The following parameters (the name within brackets refers to later abbreviations of the variables) are registered through this test: Maximum force (F1LU, N), first peak with 0.5N threshold; Deformation for F1 (D1, mm);

Hardness (SLOPE1LU, N/mm) force-deformation slope for F1LU and D1; Force for maximum deformation, 2.5mm (F2LU, N); Degree of plasticity, calculated as the percentage of plastic deformation over the total deformation; Juice area (JUICEARE, mm^2) recovered in the filter paper placed underneath the probe during the test.

Table 1. Samples measured, harvest/storage treatment, expected (*a priori*) textural state and wavelengths measured with TDRS equipment. Magness-Taylor penetration ranged from 16-22N for Cox and 14-19.5N for Golden.

Apple	# measurements	Origin	Treatment	Expected state	TDRS Far VIS λs (nm)	TDRS NIR λs (nm)
Cox	40	Belgium	ULO storage, 16 days	"fresh"	672, 750, & 818	900-1000 (each 10nm)
Cox	40	Belgium	RH 95%, 20°C, 16 days	"mealy"	672, 750, & 818	900-1000 (each 10nm)
Golden Delicious	50	Spain	Late harvest	"fresh"	672, 750, & 818	900-1000 (each 10nm)
Golden Delicious	50	Spain	Late harvest (overripe)	"mealy"	672, 750, & 818	900-1000 (each 10nm)
Total:	180					

RESULTS

Using the variables extracted from confined compression, the samples were labeled in a) four textural stages ("mealy", "dry" but firm, "soft" but juicy, "fresh"), b) three stages ("mealy", "nonmealy" = dry or soft, "fresh") and c) two stages ("mealy", "fresh"). A sample was labelled as "soft" when SLOPE1LU<20 N/mm; it was "dry" if JUICEARE<$4cm^2$; a "mealy" sample has to be soft and dry. New variables were added to the analysis (MEALY4, MEALY3 and MEALY) with the codes of this posterior classifications of samples into mealy stages.

A first comparison can be done between a priori and destructive classification, as shown in figures 1 & 2. More mealy samples were obtained for Golden than for Cox (fig.1). It can be seen (fig, 2) that, although the a priori selection of samples was mostly correct (most of the first ones resulted in "a posteriori" mealy samples, and most of the second group were finally fresh apples), an important group of supposed mealy samples were identified as dry apples, but not really mealy.

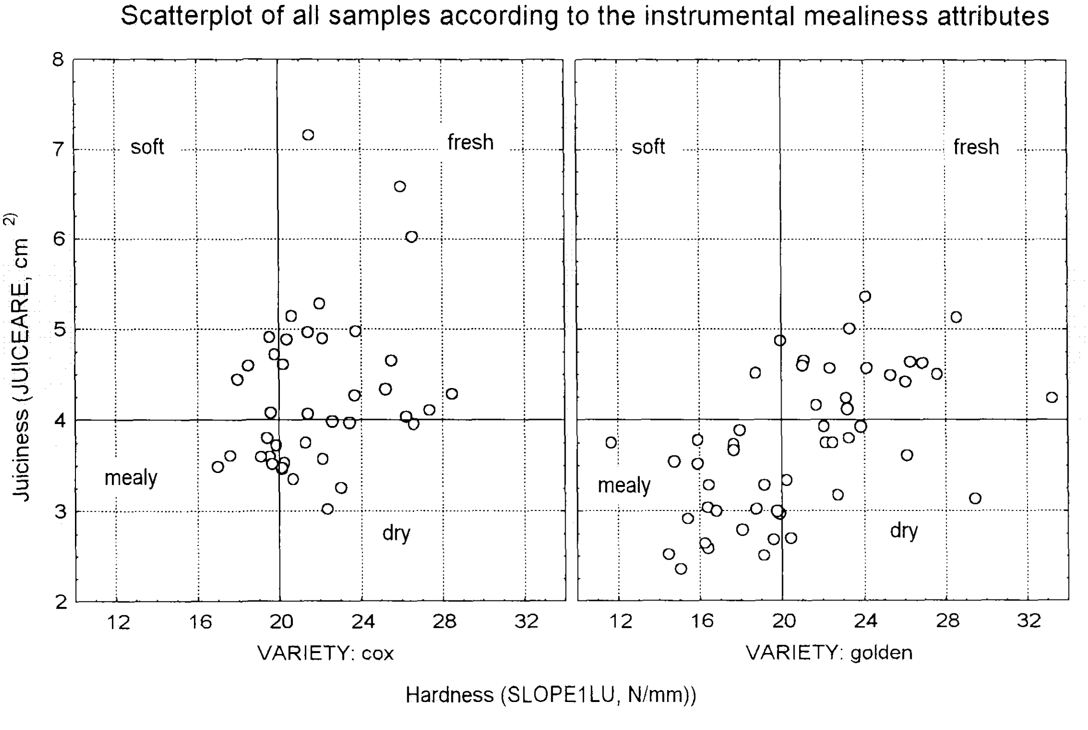

Figure 1. Hardness vs. juiciness of all samples; discriminating limits for "dry" textural category, "soft" and the combination of both ("mealy") are drawn.

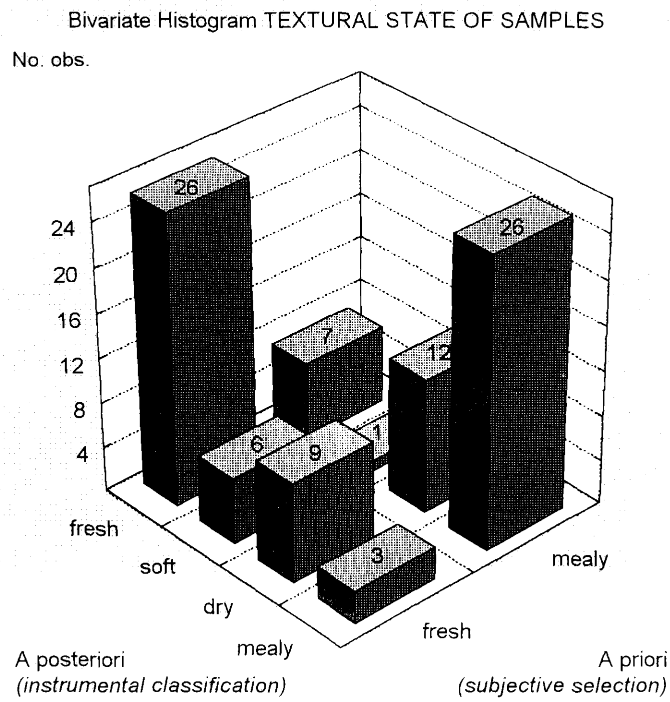

Figure 2. Comparison between the a priori selection of samples as ("mealy" or "fresh") with final textural instrumental state into four categories.

Discriminant analysis (DA) functions were built using the TDRS coefficients (variables MA672 to MA1000, and MS672 to MS1000) as explanatory variables for the classification of samples into: a) two textural categories (mealy vs, fresh), b) three (mealy, nonmealy, fresh), or c) four (mealy, dry, soft, fresh). The classification functions were modelled with a stepwise approach, selecting or removing each variable by the analysis of the unique contribution of the respective variable to the discriminatory power of the model. The numbers of individuals in each stage were not homogeneous, and partial classification scores obtained for each category were uneven; thus the global score of well classified samples in every model is a weighed average, proportional to group sizes. The relative proportions of samples (also called "a priori classification probabilities" in the DA) were p=0.68 and p=0.32, for the "fresh" and "mealy" categories in the dichotomic classification.

A first model was created using the pooled data of both varieties together for the discrimination between "mealy" and "fresh" states. 7 TDRS variables were used in the model achieving a percentage of correctly classified individual fruits of 90.0%. More misclassifications were obtained proportionally for mealy samples incorrectly predicted as fresh (8/21), than the opposite case (5/56).

Table 2. Classification matrix for apples (Cox & Golden) as "mealy" or "fresh" (= not mealy) using 7 TDRS variables. Rows: Observed. Columns: Predicted..

	fresh	mealy	Percent correct
fresh	56	5	91.80%
mealy	8	21	72.41%
Total	64	26	**85.56%**

The seven variables in the classification functions were both absorption coefficients and scattering coefficients at the chlorophyll absorption peak (670nm) and a wide range of NIR wavelengths.

The segregation ability of this type of model was internally validated (table 3) using alternatively half of the samples as the learning subset and the other half as the anonymous subset. A randomisation algorithm was used to generate the subsets conforming a distribution of 33 fresh plus 13 mealy per group.

Table 3. Validation iterations with the classification model containing 7 TDRS variables.

Iteration	"Fresh" percent correct	"Mealy" percent correct	Total percent correct
1	93,10%	81,25%	88,89%
2	78,13%	76,92%	77,78%
3	90,63%	69,23%	84,44%
4	89,66%	50,00%	75,56%

When trying to estimate a higher number of mealiness stages, the performance of the new models decreased considerably from 85% to ~72-73%. The model estimating MEALY3 ("fresh", "nonmealy" and "mealy") scored 72.2% of well classified fruits on the pooled data of both varieties, while the estimation of MEALY4 ("fresh", "dry", "soft" and "mealy") achieved 73.3%. In both cases it was noticed that the central classes ("dry", "soft" or the union of them ="nonmealy") were the worst predicted groups. It is interesting the slightly better score obtained for MEALY4 than MEALY3, which can be attributed to border effects of a small number of samples coincident with inter-classes limits, that were better allocated in the 3-stages classification.

In order to reduce the number of variables in the models, new analysis was performed with more restrictive conditions in the number of wavelengths and the tolerance level of the stepwise method. It was seen that all the remaining variables in the models were absorption coefficients, and all the scattering ones were removed in the stepwise algorithm. The wavelengths remained around the 670nm peak and the centre-left of the NIR region studied (960-980nm). Overall segregation ability for the estimation of two textural stages with 5 TDRS variables and with 3 TDRS variables are shown in tables 4 & 5.

Table 4. Classification matrix for apples (Cox & Golden) as "mealy" or "fresh" (= not mealy) using 5 TDRS variables. Rows: Observed. Columns: Predicted.

	fresh	mealy	Percent correct
fresh	55	6	90.16%
mealy	8	21	72.41%
Total	63	27	**84.44%**

Table 5. Classification matrix for apples (Cox & Golden) as "mealy" or "fresh" (= not mealy) using 3 TDRS variables. Rows: Observed. Columns: Predicted.

	fresh	mealy	Percent correct
fresh	56	5	91,80%
mealy	10	19	65,52%
Total	66	24	**83,33%**

Separate models were also built for each variety, to discriminate between two mealy stages (tables 6 & 7). In the case of Cox apples the classification score was significantly higher (95%) than the one with the pooled data, but for Golden apples the score dropped to 80%.

Table 6. Classification matrix for Golden apples as "mealy" or "fresh" (= not mealy) using 7 TDRS variables. Rows: Observed. Columns: Predicted.

	fresh	mealy	Percent correct
fresh	23	5	82.14%
mealy	5	17	77.27%
Total	28	22	**80.0%**

Table 7. Classification matrix for Cox apples as "mealy" or "fresh" (= not mealy) using 7 TDRS variables. Rows: Observed. Columns: Predicted.

	fresh	mealy	Percent correct
fresh	32	1	96.96%
mealy	1	6	85.71%
Total	33	7	**95.00%**

DISCUSSION

As it has been observed in other studies, the obtaining process of mealy samples to carry out research is not always a straight forward routine. The Cox samples stored under strict relative humidity and temperature conditions to promote mealiness development, not always show at the end of the treatment a mealy stage. In fact, a low percentage of them were found as mealy in this study, a result supported previously by other authors. This may indicate that there are more factors affecting mealiness that just the humidity and temperature during storage, harvest date and variety. On the other hand, it seems clear that late harvested Golden apples can develop mealiness by themselves and already "in the tree", without a shelf life. This is of high importance for apple growers when, due to climatic conditions or labour problems, they can not pick all the harvest on time, leaving part of it on the orchard.

The predictive models that estimate two instrumental mealiness states using absorption and scattering TDRS coefficients show high discrimination performance when classifying samples from both apple varieties (85%; 7 variables used). The stability of this performance in the validation process is good and it only decreases in one case, affected mainly by a misclassification of the "mealy" group (75%) that has to be studied further.

Models estimating more than two states offer much lower segregation abilities. The prediction of four stages shows a score of 72%, and the prediction of three gives a percentage of 73% of well classified fruits. This figures are not suitable for a classification technique. The fact that the highest misclassification scores were found in the central groups (fruits other than really mealy or really fresh) suggests that the use of the TDRS technique itself is not adequate to detect the individual quality parameters involved in the development of mealiness (apparent drought of tissues, softening) but it is useful when they are combined. It can be also a problem of the system set-up or just a matter of detection resolution, and wok is being carried out in this way.

The trial with less number of variables in the models was satisfactory, reducing the performance in just a 2% from 7 variables (7 correspondent wavelengths) to the last model with 3 variables and wavelengths. This point will be of great importance when the system will be scaled down to fit industry requirements of low cost, ease of operation and stability.

Given the differences in mealiness treatments among the varieties, the results of the classification models applied to the pooled data from both of them, show that a real cause-effect may be detected by this technique, related to the "separated cells" and "dryness" of mealiness. The development of separate models for the varieties is a logical step ahead in the process, and the first attempts show different results for the two of them: while Cox enhances the classification, Golden is unable to obtain better score than the pooled data. Anyway, these varietal models must not be taken into account deeply as the number of data used to build the models is reduced at the same time that many variables are used, which lowers the confidence on their performance.

CONCLUSIONS

Time domain reflectance spectroscopy has been proven to be a useful technique to identify mealiness in apples non destructively. Error rates in classification models discriminating mealy samples from nonmealy ones are low. The segregation between more than two textural stages of mealiness (other than “fresh” and “mealy”) can not be achieved so far, and requires more studies. The technique, new in the field of food sensors, shows interesting potentials for internal parameter detection of quality attributes and disorders.

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REFERENCES

ABBOTT, J.A. 1999. Quality measurement of fruits and vegetables. Postharvest Biology and Technology *15*(3), 207-25

AHRENS, M. and HUBER, D. 1987. A method for measuring mealiness in tomato fruit. Vegetable Crops Dept., University of Florida FL 32611.

BARREIRO, P., ORTIZ, C., RUIZ ALTISENT, M., DE SMEDT, V., SCHOTTE, S., BHANJI, Z., WAKELING, I. and BEYTS, P. K.. 1998. Comparation Between Sensorial and Instrumental Measurements for Mealiness Assessment in Apples. A Collaborative Test. J. Texture Studies *29*: 509-25.

BARREIRO, P., RUIZ-CABELLO, J., FERNÁNDEZ-VALLE, M.E., ORTIZ, C. and RUIZ-ALTISENT, M.. 1999. Mealiness Assessment in Apples Using MRI Techniques. Magnetic Resonance Imaging *17* (2), 275-81.

CUBEDDU R; MUSOLINO M; PIFFERI A; TARONI P; and VALENTINI G. 1994a. Time-Resolved Reflectance: A Systematic Study for Application to the Optical Characterization of Tissues. IEEE Journal of Quantum Electronics *30*(10), 2421-30.

CUBEDDU, R., MUSOLINO, M., PIFFERI, A., TARONI, P., VALENTINI, G. and CANTI, G. 1994b. Absorption Spectrum of Hematoporphirin Derivative *in vivo* in a Murine Tumor Model. Photochemistry and Photobiology *60*(6), 582-85.

CUBEDDU, R., A. PIFFERI, P. TARONI, G. VALENTINI, A. TORRICELI, C. VALERO, M. RUIZ-ALTISENT, AND C. ORTIZ. 1999. Non-destructive measurements of the optical properties of fruits by means of time-resolved reflectance. Proc. of Photonics West '99 - BiOS, Optical Tomography and Spectroscopy of Tissues.

DE SMEDT, V., PAUWELS, E., DE BAERDEMAEKER, J. and NICOLAÏ, B.M.. 1998. Microscopic observation of mealiness in apples: a quantitative approach. Postharvest Biology and Technology *14*, 151-158.

DE SMEDT, V. 2000. Measurement and modelling of mealiness in apples. Katholieke Universiteit Leuven, Leuven, 197 pp.

FISHER, D. V. 1943. Mealiness and quality of Delicious apples affected by growing conditions, maturity and storage techniques. Science in Agriculture *23,* 569-588.

GROSS, K.C. and SAMS, C. E. 1984. Changes in cell wall neutral sugar composition during fruit ripening: a species survey. Phytochemistry.; *23*, 2457-2461.

HARKER, F. R. and HALLETT, I. C. 1992. Physiological changes associated with development of mealiness of apple during storage. HortScience *27,* 1291-1294.

HARKER, F. R., STEC, M. G. H., HALLET, I. C. and BENETT, C. L. 1997. Texture of parenchymatous plant tissue: a comparison between tensile and other instrumental and sensory measurements of tissue strength and juiciness. Postharvest Biology and Technology.; *11,* 63-72.

ORTIZ, C.; BARREIRO, P.; RUIZ-ALTISENT M.; and RIQUELME , F. 1999. An Identification Procedure of Woolly Soft-flesh Peaches (cv. Maycrest) by Instrumental Assessment. Journal of Agricultural Engineering Research *76*(4), 355-362.

ORTIZ, C.; BARREIRO, P.; CORREA, E.; RUIZ-ALTISENT M.; and RIQUELME , F. 1999. Non-Destructive Identification of Woolly Peaches Using Mechanical Impact Response and NIR Spectroscopy. Journal of Agricultural Engineering Research *77*(2) (in press)

SONEGO, L., BEN-ARIE, R., RAYNAL, J., and PECH, J. C. 1995. Biochemical and physical evaluation of textural characteristics of nectarines exhibiting woolly breakdown: NMR imaging, X-ray computed tomography and pectin composition. Postharvest Biology and Technology. *5*(3), 187-198.

VALERO, C., RUIZ-ALTISENT, M., CUBEDDU, R., PIFFERI, A., TARONI, P., TORRICELLI A., VALENTINI, G., JOHNSON, D., and DOVER, C.. 2000. Models for Internal Quality Sorting of Fruit, Based on Time-Domain Laser Reflectance

Spectroscopy (TDRS). Proc. of AgEng2000 Conference on Agricultural Engineering, Warwick. 00-PH-002.

VON MOLLENDORF, L. J., JACOBS, G., and VILLIERS, O. T. 1992. Post-harvest factors involved in the development of chilling injuries in peaches and nectarines. Journal of South African Society of Horticultural Science *5*(2), 58-66.

VON MOLLENDORF, L. J., VILLIERS, O. T., JACOBS, G., and WESTRAAD, I. 1993. Molecular characteristics of pectic constituents in relation to firmness, extractable juice, and woolliness in nectarines. Journal of the American Society of Horticultural Science *118*, 77-80.

VERLINDEN, B. E., NICOLAÏ, B. M, and DE BAERDEMAEKER, J. 1997. Modelling the relation between macroscopic vegetable tissue strength and the strength of cell walls and middle lamellae: a stochastic approach. ASAE Paper 976025.