MEALINESS DETECTION IN APPLES USING TIME RESOLVED REFLECTANCE SPECTROSCOPY

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ABSTRACT

Mealiness is a textural attribute related to internal fruit disorder that is characterized by the combination of abnormal softness of the fruit and absence of free juiciness in the mouth when eaten by the consumer. Time-resolved laser reflectance spectroscopy was used as a tool to determine mealiness. This new technique in agrofood research may provide physical and chemical information independently and simultaneously, which is relevant to characterize mealiness. Using visible and near infrared lasers as light sources, time-resolved laser reflectance spectroscopy was applied to Golden Delicious and Cox apples ($n = 90$)*, to characterize batches of untreated samples and samples that were stored under conditions that promote the development of mealiness (20C & 95% RH). The collected database was clustered into different groups according to their instrumental test values. The optical coefficients were used as explanatory variables to build discriminant functions for mealiness. The performance of the classification models created ranged from 47 to 100% of correctly identified mealy versus nonmealy apples.*

KEYWORDS

Apple, laser reflectance spectroscopy, mealiness, near infrared spectroscopy, time-resolved spectroscopy, visible spectroscopy

INTRODUCTION

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 feeling of disaggregated tissue with lack of juiciness. It is a consequence of a biochemical process resulting in pectin degradation in the middle lamellae (Gross and Sams 1984; Von Mollendorf *et al.* 1993), and their consequences are visible by microscopic observation (De Smedt *et al.* 1998). Mealiness is associated with late harvest and long-term storage (Fisher 1943; Harker and Hallett 1992). Mealiness onset may also be accelerated by temperature treatments (Von Mollendorf *et al.* 1992) combined with extremely high relative humidity (De Smedt 2000).

The characterization of mealiness has been done traditionally by means of sensory panels defining and grading sensorial descriptors (Bignami *et al.* 2003). However, relations between physiology changes, fruit texture and sensory measurements of tissue strength and juiciness have been established successfully (Paoletti *et al.* 1993; Harker *et al.* 1997; Verlinden *et al.* 1997). Correlations of sensory attributes (crispness and juiciness, at first bite and during chewing) to a combination of parameters measured using instrumental tests (confined compression of probes) have been established. Within the same work (Barreiro *et al.* 1998) a redefinition of mealiness in apples and peaches in terms of rheological properties was proposed following sensory descriptors in mealiness perception. A new instrumental mealiness scale was created, based on a combination of instrumental parameters like loss of crispness, of hardness and of juiciness, which is able to characterize objectively the mealiness state of a given sample and correlates well with sensory mealiness (Barreiro *et al.* 1998). More studies can be found also relating to peaches (Sonego *et al.* 1995; Ortiz *et al.* 1999) and tomatoes (Ahrens and Huber 1987).

Several nondestructive methods for instrumental mealiness measurement of peaches, apples and tomatoes have been attempted using different techniques: near infrared spectroscopy (NIR) spectroscopy combined with low mass impact (Ortiz *et al.* 2001), acoustic impulse response (De Smedt 2000), ultrasonic wave propagation through fruit tissues (Bechar *et al.* 2005) and nuclear magnetic resonance (NMR) (Barreiro *et al.* 1999). Nevertheless, the development of stand-alone nondestructive techniques is still needed, especially if they are fast and if they could be engineered into an automatic on-line classification system (Abbott 1999).

Time-resolved reflectance spectroscopy (TRS) is a nonconventional spectroscopic technique that has been developed for use in medicine (Cubeddu *et al.* 1994a) to characterize the optical properties of tissues, and to locate discontinuities and affected areas like human and animal tumors. Among its advantages compared with more traditional spectroscopic techniques, there is the feasibility to derive simultaneously two (in principle) independent optical parameters: the absorption of the light inside the irradiated body, and the scattering of the photons across the tissue. For each wavelength, TRS generates two coefficients (μ_a, absorption coefficient; and μ'_s, transport scattering coefficient). Both are dependent on wavelength. By measuring at consecutive wavelengths two arrays of values, an absorption spectrum and a "scattering spectrum," can be obtained. The working hypothesis of the present work was that these coefficients are related, respectively, to chemical components (μ_a) and to physical properties (μ'_s) of the sample. Therefore, TRS can be applied to the quantification of chemicals and the measurement of the rheological properties (or the combination of both: soft texture and dryness, i.e., mealiness) at the same time. TRS has been applied satisfactorily for the nondestructive evaluation of fruit internal quality (Valero *et al.* 2004a,b). 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 for the quantification of several aspects of fruit quality (firmness estimation, sugar content and acidity). In the present work, the objective was to apply TRS as a nondestructive inspection method for mealiness.

MATERIALS AND METHODS

Fruit Material

Two groups of samples were prepared:

(1) Apples with expected "natural mealiness." In order to enhanced the risk of mealiness or abnormal texture degradation, apples were harvested late in the season: 50 Golden Delicious apples were picked from two orchards (La Almunia de Doña Godina, Zaragoza, Spain) during the last week of October 1998 (late harvest), packed and sent to Milano (INFM) in November. Both firm and soft fruits were picked, in order to obtain all possible textural states. About half of the samples were expected to be mealy as a consequence of developing mealiness on the tree.

(2) Apples with mealiness induced in chamber storage. In this case colleagues at the Catholic University of Leuven (Belgium) prepared along the autumn samples from the Cox variety, harvested early in the season (end of September) and stored until November 1998 under specific conditions: 20 of them were kept inside an ULO chamber (ultra low oxygen) to preserve their freshness at maximum levels; and 20 apples were kept during 16 days in an atmosphere of 95% relative humidity and 20C, to promote the development of mealiness (Andani *et al.* 1999). Not all of them were expected to be finally mealy in terms of instrumental mealiness, as indicated by previous studies (Barreiro *et al.* 1998).

The reference tests (firmness and juiciness) and TRS measurements that were carried out on the samples are presented within in the same sequence as for the tests.

TRS Measurements

Time-resolved reflectance spectroscopy is based on the measurement of the broadening of a short light pulse, transmitted across a turbid medium (fruit tissues) (Cubeddu *et al.* 1994b). The TRS equipment used in this work is described in detail in the study by Cubeddu *et al.* (2001a,b). A simplified scheme of it is shown in Fig. 1. The light source is a laser beam, therefore monochromatic, but tunable at several wavelengths. The light is injected in the fruit through the intact skin by means of fiber optics positioned orthogonal 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 another fiber placed at 20 mm distance (Fig. 2). The optical paths of the photons with larger probability of being recovered after suffering internal reflection form a three-dimensional light region with a semitoroidal shape inside the apple, constructed from the incoming fiber contact point to the recovering fiber contact point on the skin. If an adequate theoretical model is used for the experimental analysis of data and several hypotheses 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 (Cubeddu *et al.* 1994a). In our case, the diffusion theory (Eq. 1) was considered to process the TRS data points, and the curve with the best fit was obtained by iteration: μ_a and μ'_s are derived from the curve (Fig. 3). Notation in Eq. (1) is: $\phi(\rho, t)$, photon fluence rate; $S(\rho, t)$, photon source: ρ, radial position; t, time; n, index of refraction; c, speed of light in vacuum. Detailed description is given in the study by Cubeddu *et al.* (1994a).

$$\frac{n}{c}\frac{\partial}{\partial t}\phi(\rho,t)-[3(\mu_a+\mu_s')]^{-1}\cdot\nabla^2\phi(\rho,t)+\mu_a\phi(\rho,t)=S(\rho,t) \qquad (1)$$

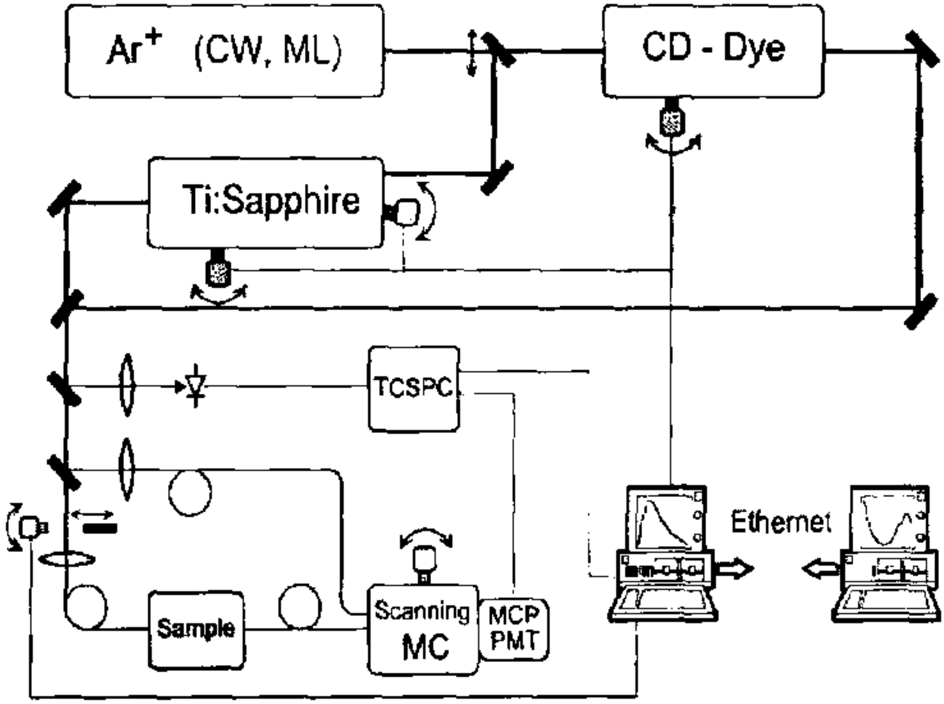

FIG. 1. SCHEME OF THE SYSTEM SET UP FOR TRS MEASUREMENTS AT INFM LABORATORY: LINES INDICATE OPTICAL PATHS (FIBER OPTICS) FROM THE LASERS (ARGON, DYE AND TITANIUM:SAPPHIRE) THROUGH THE SAMPLE AND TOWARDS THE DETECTOR (MULTICHANNEL PLATE PHOTOMULTIPLIER, MCP PMT), OTHER COMPONENTS: TIME-CORRELATED SINGLE PHOTON COUNTING UNIT (TCSPC), SCANNING MONOCROMATOR (MC) (CUBEDDU *ET AL.* 1994A)

For this study, the absorption and transport scattering coefficients of both sides of each sample were registered at several wavelengths: far-visible (672, 750 and 818 nm using diode lasers as light sources) and NIR (from 900 to 1000 nm, at steps of 10 nm using a tunable laser). The notation for these variables is as follows: "$\mu_{a,672}$" for absorption coefficient at 672 nm, "$\mu_{s,672}$" for transport scattering coefficient at 672 nm, and so on.

Mechanical Measurements

A confined compression test was carried out for instrumental mealiness assessment. Using a texture analyzer (TA.XT2, Stable Micro Systems Ltd, Surrey, UK) a maximum deformation of 2.5 mm was applied at 20 mm/min deformation rate on cylindrical probes of 1.7 cm height and diameter. Deformation was immediately removed at the same rate; two measurements were

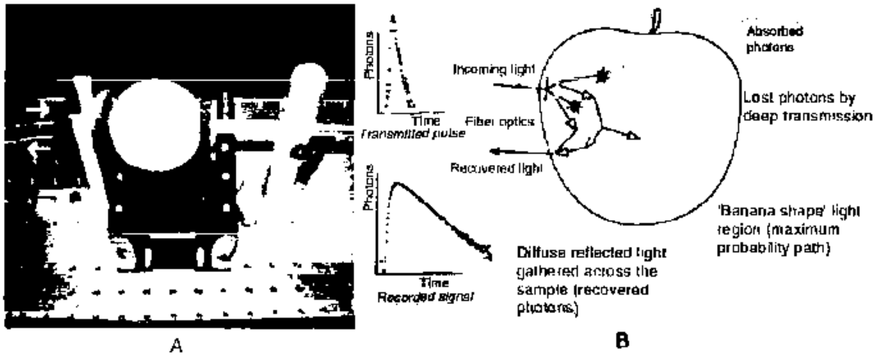

FIG. 2. SCHEME OF THE SAMPLE PRESENTATION FOR TRS MEASUREMENTS
(A) Fruit holder with incoming fiber and outcoming fiber (white arrows in photo) in contact with fruit skin. (B) A pulse of photons was pumped through the incoming fiber and the photons not suffering absorption or deep transmission were recovered.

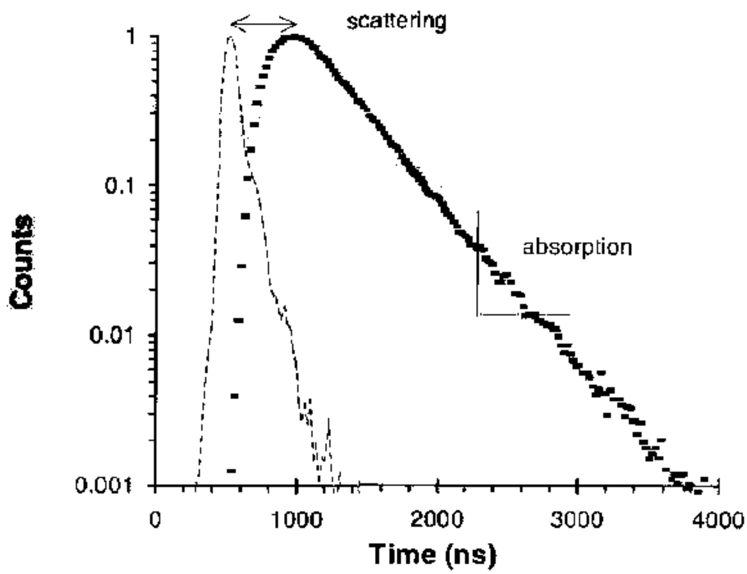

FIG. 3. TYPICAL DATA OBTAINED WITH TRS TECHNIQUE: INJECTED PULSE (NARROW PEAK) AND REMITTED PULSE (BROADER CURVE, NORMALIZED TO THE PEAK INTENSITY) ARE LATER BEST-FITTED TO DIFFUSION THEORY TO OBTAIN SCATTERING AND ABSORPTION COEFFICIENTS (CUBEDDU *ET AL.* 1994A)

made per fruit (one per side) using the average for the subsequent analyses for this load/unload test. Cylinders were confined in a disk that had a hole of the probe size. The rod used for the compression test was 15.3 mm diameter to avoid any contact with the disk during testing. A filter paper (Albet n° 1305 of 77.84 g/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 area of the juice spot was measured later on using conventional image analysis equipment (Hitachi CCD black and white camera, Tokyo, Japan). The outline of the juice spot on the filter paper was extracted (Image Pro Plus software, Media Cybernetics Silver Spring, MD) and the area inside it was used as indicator of juiciness. The variables registered with this test and used in the statistical analyses (abbreviations of the variables within brackets) are: hardness of the sample ("S," N/mm) expressed as the slope of the force-deformation curve during confined loading, and the juice area ("J," mm^2) recovered in the filter paper placed underneath the probe during the test.

Using the variables extracted from confined compression, the samples were labeled according to their instrumental mealiness stage, as a combination of two possible hardness states (firm, not firm) with two possible juiciness states (juicy, nonjuicy). A sample was considered "not firm" when $S < 20$ N/mm, and "firm" otherwise. Besides it was labeled "nonjuicy" when $J < 4$ cm^2, and "juicy" otherwise (Barreiro *et al.* 1998). Instrumental definition of mealiness requires a sample to be "not firm" and "nonjuicy" simultaneously (Table 1).

Statistical Analysis

As a first step, linear correlations between TRS variables, hardness and juiciness were analyzed. Because of the poor regression results (see Results section) and the fact that the aim was matching a categorical instrumental mealiness scale using TRS information, the statistical approach was switched to a classification algorithm.

Following an industry-oriented application for the TRS technique, a pass/fail classification was searched for. Discriminant analysis technique was

TABLE 1.
NOTATION OF FRUIT CATEGORIZATIONS ACCORDING TO THE DESTRUCTIVE INSTRUMENTAL MEALINESS STATE: "FIRM" SAMPLE WHEN $S > 20$ N/mm; "JUICY" SAMPLE IF $J > 4$ cm^2. SAME GRAY TONE INDICATES MEMBERSHIP OF SAME GROUP

	Two classes		Three classes		Four classes	
	Nonjuicy	Juicy	Nonjuicy	Juicy	Nonjuicy	Juicy
Not firm	"Mealy"	"Nonmealy"	"Mealy"	"Nonmealy"	"Mealy"	"Soft"
Firm	"Nonmealy"	"Nonmealy"	"Nonmealy"	"Fresh"	"Dry"	"Fresh"

used as the statistical tool used to create the classification models. Classification functions were built 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 discriminatory ability of the models was evaluated either comparing the percentage of well-classified samples obtained with every model, or calculating the *similarity index*, K (Eq. 7) used by Steinmetz *et al.* (1996) as a measurement of the agreement between two instrumental classifications. K calculation starts from a classification matrix that is converted into a probability matrix where p_{ii} is the probability of a sample to be classified by method A and B into the same category i. The probabilities p_{ij} (that method A classifies an object into category i whereas method B classifies the same object into category j) are computed as stated in Eq. 2. Thus, θ_1 (Eq. 5) is the sum of coincident probabilities (along the main diagonal of the probability matrix: p_{ii}) and θ_2 (Eq. 6) is the sum of the products of the accumulated probability of being in each row or column (p_{i+} is the accumulated probability of being in row i, whereas p_{+i} is the accumulated probability of being in column j, Eqs. 3 and 4).

$$p_{ij} = \frac{n_{ij}}{n} \tag{2}$$

$$p_{i+} = \sum_{j=1}^{q} p_{ij} \tag{3}$$

$$p_{+i} = \sum_{j=1}^{q} p_{ji} \tag{4}$$

$$\theta_1 = \sum_{i=1}^{q} p_{ii} \tag{5}$$

$$\theta_2 = \sum (p_{i+})(p_{+i}) \tag{6}$$

$$K = \frac{\theta_1 - \theta_2}{1 - \theta_2} \tag{7}$$

In this work the K index is used to compare the destructive classification procedure with the nondestructive TRS method of classification. The advantage of using this similarity index is that, from the absolute proportion of cases where the methods agree (θ_1), it subtracts the proportion of cases where the methods agree purely by chance (θ_2).

Classification models were created first for the pooled database, joining both apple varieties. Varietal models were also created in a second phase. In all the cases, calibration of the classification models was performed using half of the samples for the discriminant analysis. Validation of the models was carried out with the rest of the database.

For the creation of the classification models, in a first approach only two fruit states were used in order to create two-group classifications: "mealy" and "nonmealy." A "mealy" sample was not firm and nonjuicy at the same time, whereas "nonmealy" samples gathered all the other possible combinations, in this first analysis.

Further approaches included classification models with samples classified into: (1) three states ("mealy" [nonjuicy and not firm], "nonmealy" [nonjuicy or not firm], "fresh" [juicy and firm]); and (2) four textural states ("mealy" [nonjuicy and not firm], "dry" but firm, "soft" but juicy, "fresh" [juicy and firm]). Table 1 synthesizes the notation used for each combination of hardness and juiciness states, when creating two-group, three-group or four-group models.

RESULTS

Linear Relation between Destructive and Nondestructive Variables

Linear correlation between the variables extracted from the destructive test (hardness and juiciness) and the nondestructive measurements (TRS absorption and scattering coefficients) was analyzed. In Fig. 4, a selection of TRS variables is presented in the form of a graphical correlation matrix. Correlation coefficients were low ($r < 0.4$) in any case. Internal correlation in the TRS data (inside absorption spectra, scattering spectra, or between absorption and scattering coefficients) was high ($r = 0.9$) in most cases. Correlation was expected between absorption variables (as is normal within NIR spectra); however, correlation was not expected to be so high between scattering and absorption parameters, as they refer to different physical phenomena.

Destructive Classification of Samples according to Instrumental Mealiness

Figure 5 shows the result of fruit classification into: firm, soft, dry and mealy. A higher number of mealy samples was obtained for Golden (22 out of 50) than for Cox (7 out of 40; Fig. 5). A wider range of texture variation was found for Golden than for Cox, in this case. Cox is a typical example of mealiness susceptible variety with very erratic mealiness onset, which is

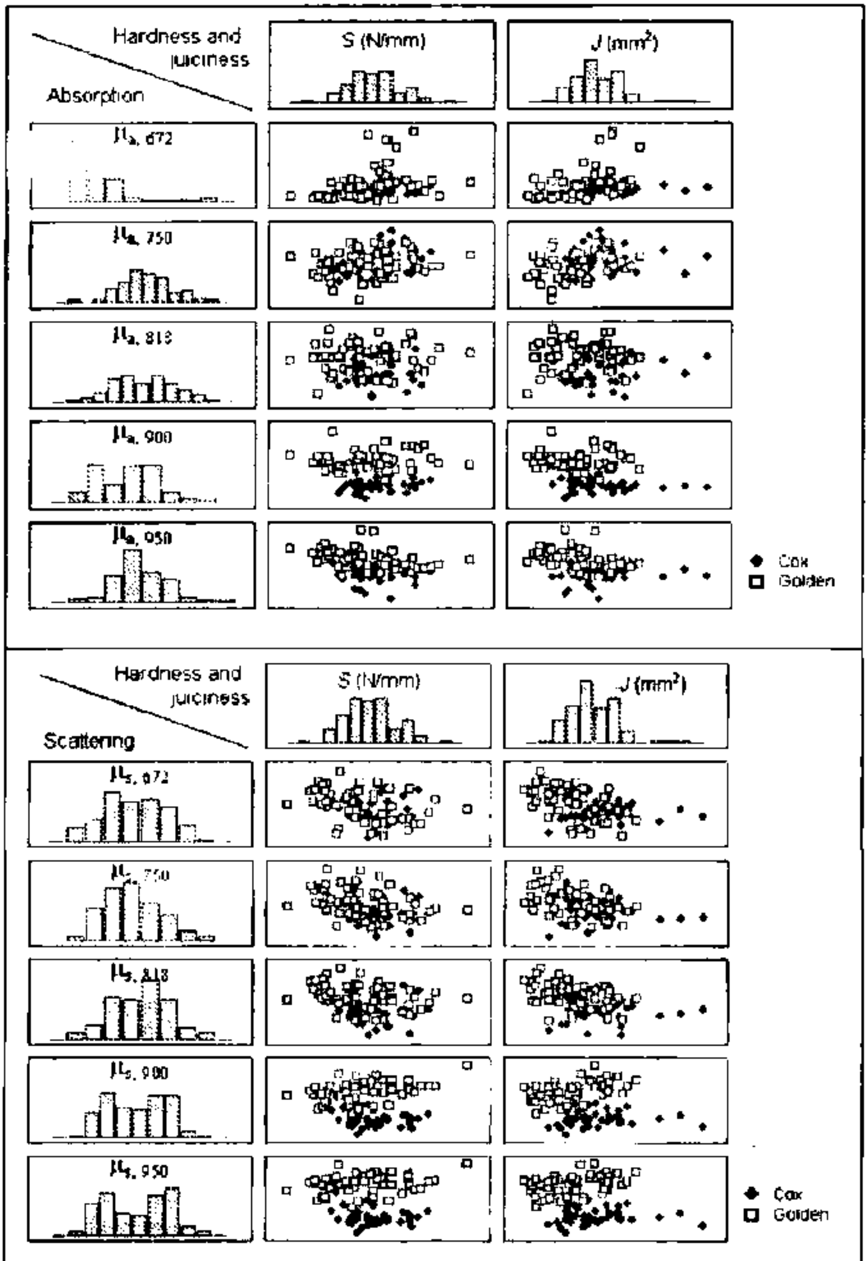

FIG. 4. HISTOGRAMS AND CORRELATIONS BETWEEN SELECTED TRS VARIABLES
Horizontal axes: the first column of scatterplots, the slope (S, N/mm) of the curve during the mechanical test is presented; the second column, the juice area recovered (J, mm^2). Vertical axes: absorption and transport scattering TRS coefficients, at several wavelengths.

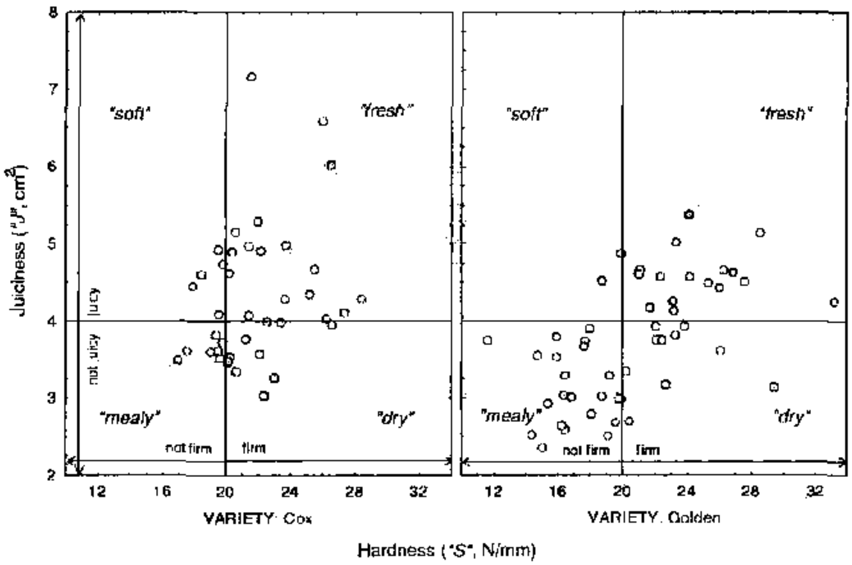

FIG. 5. HARDNESS VERSUS JUICINESS OF TESTED APPLES: LINES INDICATE DISCRIMINATING LIMITS FOR "DRY" TEXTURAL CATEGORY (JUICINESS < 4 cm³), "SOFT" (HARDNESS < 20 N/mm) AND THE COMBINATION OF BOTH ("MEALY")

confirmed in this case. Textural disorder in batches being dry and soft for Cox lacks from a comparable cell disaggregation status.

Models to Classify Nondestructively Samples Using TRS

Discriminant analysis functions were built using selected TRS coefficients (variables $\mu_{a,672}$ to $\mu_{a,1000}$, and $\mu_{s,672}$ to $\mu_{s,1000}$) as explanatory variables for the classification of samples into (Table 1): (1) two textural categories ("mealy" versus "nonmealy"), (2) three textural categories ("mealy," "nonmealy," "fresh"), or (3) four textural categories ("mealy," "dry," "soft," "fresh"). The number of individuals in each stage was 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.

A first model was calibrated using half of the pooled data of both varieties for the discrimination between "mealy" and "nonmealy" states. Fifteen TRS variables were used in the model achieving a percentage of correctly classified individual fruits of 98%. Validation with the rest of the database (Table 2) resulted in 80% of the samples correctly classified. More misclassifications

TABLE 2.
VALIDATION CLASSIFICATION MATRIX FOR APPLES (COX AND GOLDEN) AS "MEALY" OR "NONMEALY" USING 15 TRS VARIABLES AND HALF OF THE DATABASE. GRAYED AREAS DENOTE CORRECT CLASSIFICATIONS. ROWS: OBSERVED BY MECHANICAL MEASUREMENTS. COLUMNS: PREDICTED BY TRS

	Nonmealy	Mealy	% Correct
Nonmealy	**26**	6	82
Mealy	3	**10**	77
Total	29	16	80

TABLE 3.
VALIDATION CLASSIFICATION MATRIX FOR APPLES (COX AND GOLDEN) AS "MEALY," "NONMEALY" OR "FRESH." GRAYED AREAS DENOTE CORRECT CLASSIFICATIONS. ROWS: OBSERVED BY MECHANICAL MEASUREMENTS. COLUMNS: PREDICTED BY TRS

	Fresh	Nonmealy	Mealy	% Correct
Fresh	**9**	5	3	53
Nonmealy	2	**7**	6	47
Mealy	2	4	**7**	54
Total	13	16	16	51

were proportionally obtained for mealy samples incorrectly predicted as fresh (1/15 in the calibration and 3/10 in the validation, lack of sensitivity), than the opposite case (0/29 and 6/26, lack of specificity).

The 15 variables in the classification functions were mostly absorption coefficients and some scattering coefficients, at wavelengths around the chlorophyll absorption peak (670 nm) and a wide range of NIR wavelengths (818, 900, 930, 940, 960 and 980 nm).

When trying to estimate three texture stages ("fresh," "nonmealy" and "mealy") with TRS, the performance of the new models decreased considerably from 98 to 71%. Moreover, validation only achieved 51% (Table 3). The estimation of four textural stages ("fresh," "dry," "soft" and "mealy") achieved 71% in the calibration model, but only 47% in the validation (Table 4). In both cases it was noticed that the "mealy" category was best predicted than the other groups ("fresh," "dry," "soft" or the combination of them, i.e., "nonmealy").

In order to reduce the number of variables in the models to enhance robustness, new analyses were performed with more restrictive conditions in the number of wavelengths and the tolerance level of the stepwise method. It

TABLE 4.
VALIDATION CLASSIFICATION MATRIX FOR APPLES (COX AND GOLDEN) AS "MEALY," "SOFT," "DRY" OR "FRESH." GRAYED AREAS DENOTE CORRECT CLASSIFICATIONS. ROWS: OBSERVED BY MECHANICAL MEASUREMENTS. COLUMNS: PREDICTED BY TRS

	Fresh	Soft	Dry	Mealy	% Correct
Fresh	7	1	5	4	63
Soft	1	1	3	0	50
Dry	2	0	3	5	64
Mealy	1	1	1	10	86
Total	11	3	12	19	47

TABLE 5.
VALIDATION CLASSIFICATION MATRIX FOR APPLES (COX AND GOLDEN) AS "MEALY" OR "NONMEALY" USING FIVE TRS VARIABLES. GRAYED AREAS DENOTE CORRECT CLASSIFICATIONS. ROWS: OBSERVED BY MECHANICAL MEASUREMENTS. COLUMNS: PREDICTED BY TRS

	Nonmealy	Mealy	% Correct
Nonmealy	22	10	69
Mealy	3	10	77
Total	25	20	71

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 remaining wavelengths were around the 670 nm peak also combined with the 960–980 nm NIR region. Overall segregation ability in the estimation of two textural stages with five TRS variables and with three TRS variables were, respectively, 89% and 82%, with validations achieving 71% (Table 5) and 88% (Table 6).

Separate models were also built for each variety, to assess mealiness onset ("nonmealy" versus "mealy"). In the case of Cox apples the classification score reached 100% whereas for Golden apples the score dropped to 92%. Validations showed 80% of well-classified fruits for Cox and 68% for Golden (Table 7).

Table 8 shows the evaluation of models in terms of similarity index ("*K*" %). The subtraction of random agreement between procedures leads to poorer scores with respect to the percentage of well-classified individuals. The best

TABLE 8.

CLASSIFICATION PERFORMANCE OF THE MODELS. COMPARING THE NUMBER OF CORRECTLY CLASSIFIED FRUITS (CC) WITH THE SIMILARITY INDEX (K). AND ITS COMPONENTS: θ_1 (ABSOLUTE PROPORTION OF CASES WHERE THE DESTRUCTIVE AND TRS CLASSIFICATIONS AGREE) AND θ_2 (PROPORTION OF CASES WHERE THEY AGREE PURELY BY CHANCE)

	Model	CC (calibration) (%)	CC (validation) (%)	K (%)	K – CC (%)	θ_1	θ_2
1	90 apples (Cox and Golden) as "mealy" or "nonmealy" using 15 TRS variables	98	80	54	–26	0.8000	0.5609
2	90 apples (Cox and Golden) as "mealy" or "nonmealy" using five TRS variables	89	71	39	–32	0.7111	0.5234
3	90 apples (Cox and Golden) as "mealy" or "nonmealy" using three TRS variables	82	88	73	–15	0.8888	0.5797
4	50 Golden apples as "mealy" or "nonmealy" using seven TRS variables	92	68	33	–35	0.6800	0.5200
5	40 Cox apples as "mealy" or "nonmealy" using seven TRS variables	100	80	54	–26	0.8000	0.5609
6	90 apples (Cox and Golden) as "mealy," "nonmealy" or "fresh" using seven TRS variables	71	51	27	–24	0.5111	0.3303
7	90 apples (Cox and Golden) as "mealy," "soft," "dry" or "fresh" using seven TRS variables	71	47	25	–22	0.4666	0.2809

TABLE 6.
CLASSIFICATION MATRIX FOR APPLES (COX AND GOLDEN) AS "MEALY" OR "NONMEALY" USING THREE TRS VARIABLES. GRAYED AREAS DENOTE CORRECT CLASSIFICATIONS. ROWS: OBSERVED BY MECHANICAL MEASUREMENTS. COLUMNS: PREDICTED BY TRS

	Nonmealy	Mealy	% Correct
Nonmealy	29	3	91
Mealy	2	11	85
Total	31	14	88

TABLE 7.
CLASSIFICATION MATRICES FOR GOLDEN APPLES (UPPER PART) AND COX APPLES (LOWER PART) AS "MEALY" OR "NONMEALY" USING SEVEN TRS VARIABLES. GRAYED AREAS DENOTE CORRECT CLASSIFICATIONS. ROWS: OBSERVED. COLUMNS: PREDICTED

	Nonmealy	Mealy	% Correct
Golden			
Nonmealy	11	4	73
Mealy	4	6	60
Total	15	10	68
Cox			
Nonmealy	14	3	82
Mealy	1	2	67
Total	15	5	80

result corresponds to model 3 with a decrease of 15%. This model uses only three TRS parameters, which is a premise for less overfitting and better robustness.

DISCUSSION

As it has been observed in other studies (Barreiro *et al.* 1998; Andani *et al.* 1999), the process for obtaining mealy samples to carry out research is not always a straightforward 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 mealy using the instrumental destructive test.

This may indicate that there are more factors affecting mealiness than 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 textural disorders by themselves and already "in the tree," without shelf life. This is of high importance for apple growers when, because of climatic conditions or labor problems, it is impossible to pick the whole production on time, leaving part of it on the orchard.

The predictive models that estimate two instrumental mealiness states ("nonmealy," "mealy") using absorption and scattering TRS coefficients show high discrimination performance when classifying samples from both apple varieties (80% of well-classified fruits in the validation; 15 variables used in the model). The robustness in the validation process should be enhanced, both using more samples and reducing the number of variables.

Models estimating more than two textural states offer lower segregation abilities. The prediction of three and four states shows, in both cases, a score of 71% of well-classified fruits, with very poor validation results (51% and 47% of well-classified fruits, respectively). The fact that the highest misclassification scores were found in the groups other than "mealy" suggests that the use of the TRS technique itself is not adequate to detect the individual quality parameters involved in the development of mealiness (apparent drought of tissues, softening). It can be also a problem of the system set up or just a matter of detection resolution.

The attempt to reduce the number of variables in the models was satisfactory. Performance in the detection of mealiness onset ("nonmealy," "mealy") was enhanced from 80 to 88% using three variables, when the validation scores are compared. This fact confirms the increase in robustness for lower number of variables and the risk that is commonly assumed when using global models.

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 "loss of tightness in the tissues" and "dryness" associated to 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. In the case of Cox the classification is the best; in the case of Golden the model is unable to obtain a better score than the pooled data. These varietal models were created with a reduced number of fruits, and at the same time many variables are used (seven), which decreases the confidence on their robustness.

The similarity index (K) is useful to estimate the robustness of the models in terms of real segregation capacity, as it eliminates the effect of "agreement by chance." In the models presented in this work, K index punishes the performance of the models by nearly 20–30% in many cases. This indicates that: (1) the destructive quantification of instrumental mealiness is not measuring exactly the same property as TRS, because the agreement between both methods is only 70%; and (2) the model may be unstable or not repeatable enough for industrial usage. The applicability of the present models on an industrial basis (i.e., a sensor on a packing line) has to be improved, either with better models or with a complementary sensor together with sensor fusion decision algorithms.

CONCLUSIONS

Time-resolved reflectance spectroscopy has been proven to be a useful technique to identify mealiness in apples nondestructively. Error rates in classification models discriminating mealy samples from nonmealy ones are low, when considering the traditional indicator of the segregation ability (percentage of correctly classified fruits). The segregation between more than two textural stages of mealiness (other than "nonmealy" and "mealy") cannot be achieved to date. A TRS prototype to detect mealiness should be developed for on-line measurements, and sufficient data should be gathered to tune the models. The technique, new in the field of food sensors, shows interesting potential for internal parameter detection of quality attributes and disorders.

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