Determination of Mealiness in Apples using Ultrasonic Measurements

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A system based on ultrasonic energy absorbance was developed, for non-destructive measurements of three levels of texture degradation towards mealiness in Jonagold and Cox apples. The ultrasonic system comprises a high-power generator and a pair of 80 kHz ultrasonic transducers. One transducer, acting as a transmitter, sends a pulse through the apple tissue, which absorbs part of its energy, depending on internal textural attributes, and the transmitted pulse is received as an emerging signal by the other transducer. The detected ultrasound waves were analysed in parallel with the determination of the mealiness level of the fruit in accordance with destructive measurements in confined compression. The results obtained in Cox apples showed a good correlation between the ultrasound measurements and the confined-compression destructive tests for each mealiness level.

1. Introduction

In apples, texture seems to be the predominant quality attribute, together with flavour and appearance (Lapsley *et al.*, 1992). Crispness, firmness, hardness, juiciness and mealiness are the most generally recognised texture attributes in apples, and mealiness impairs the quality of apples and reduces their market value. Consumers are capable of distinguishing a mealy product from a fresh one, identifying it correctly with terms such as non-juicy, soft, *etc*. Nevertheless, there is a need for a reliable method, supported by appropriate sensors, for the non-destructive measurement and classification of apples in terms of their mealiness; furthermore, such a method must be usable by an untrained person. The demand for high-quality calls for a reliable, rapid, non-destructive, non-invasive technique for measuring some of the texture attributes of the fruit, especially mealiness; these attributes develop as the fruit matures and are indicative of its quality. Several techniques for detection and measurement of mealiness have been suggested in the literature, in addition to sensory analysis. Destructive methods include texture profile analysis (Tu & De Baerdemaeker, 1995), tensile tests (Tu *et al.*, 1996), acoustic (Abbott *et al.*, 1968) and ultrasonic wave propagation in slices of apple tissues (De Smedt, 2000); and non-destructive methods include magnetic resonance techniques (Barreiro *et al.*, 1999), acoustic impulse response (Duprat *et al.*, 1997); near infrared (NIR) (Lu & Ariana, 2002); impact and NIR (Ortiz *et al.*, 2001), and laser (Cho & Han, 1999).

A system and method based on ultrasonic energy absorbance was suggested by Mizrach *et al.* (2003) for rapid non-destructive measurement of mealiness in apples. This method is based on a patented development, which enables the fruit quality attributes to be observed by measuring the changes in ultrasonic sound waves passing through the fruit tissue over a short distance across the peel (Mizrach *et al.*, 1994).

The present paper suggests an analytical method for comparing the results obtained by an ultrasound technique with those of destructive determinations of mealiness level based on the destructive measurements of maximum force and hardness in confined compression, and on the juiciness of the apple tissue (Barreiro *et al.*, 1998).

2. Materials and methods

2.1. *Fruit selection*

Two apple varieties (*Malus domestica* Borkh L., cvs Jonagold and Cox) were selected, and 60 fruits of each cultivar were used. The fruits were picked at the fruit grower, Thielkens, in Belgium, and were treated at the Flanders Centre/Laboratory (in the Katholieke Universiteit in Leuven, Belgium) to enhance three different levels of ripening, by the application of a protocol that had been developed to produce mealy fruits (FAIR, 1998). The FAIR protocol involves subjecting the apples to various combinations of temperature, humidity and storage time. Three mealiness levels were achieved through appropriate treatments: fresh [3 °C, 95% relative humidity (RH), 26 days], ripe [3 °C, 95% RH, 16 days followed by 20 °C, 95% RH, 10 days], and overripe [20 °C, 95% RH, 26 days].

There is a well-known relationship between the preparation protocol and the onset of mealiness. However, it is necessary to examine the various development stages of mealiness in fruits individually, as not all are equally affected by the mealiness-enhancing process (FAIR protocol), therefore, the degree of mealiness at each stage was determined by a specific destructive test. Thus, the mealiness level was determined by destructive tests in confined compression (Barreiro *et al.*, 1998).

2.2. *Principles and instrumentation of ultrasonic tests*

The ultrasonic system is based on the emission of known ultrasonic energy into the fruit flesh and measurement of the ultrasonic energy received after the passage of the signal through the fruit tissue and over a short distance across the peel. The mechanical structure of the tissue, its physiochemical quality indices, and each change in the quality attributes of the fruit, affect the energy of the received signal. Previous studies found a good correlation between the attenuation of the ultrasonic signal and the mechanical and physiological changes in the fruit tissue (Mizrach *et al.*, 1994, 1996, 1997, 1999, 1999a, 1999b, 2000). It was found that there were linear correlations between the force applied and the energy absorbed in the tissue, and that the gradient of the linear correlation equation changed according to the structural and physiological changes in the fruit tissue (Mizrach *et al.*, 1997). The present experimental arrangement included mechanical, electronic and microcomputer units (*Fig. 1*). The mechanical unit comprised a pair of 80 kHz ultrasonic transducers assembled together and mounted with a known gap (about 2 mm) and angle (120°) between their tips (*Fig. 2*). Exponential Plexiglas energy concentrators were used to match each transducer (35 mm in diameter) to a chisel-type contact end (0·2 mm by 3 mm) at the fruit surface. One transducer acted as a transmitter and the other as a receiver; the transmitted pulse passed through the apple tissue, covered about 5 mm in the vicinity between the tips, in which part of its energy was absorbed, depending on internal textural attributes, and the receiver collected the transmitted signal (Mizrach *et al.*, 1994). The transmitter was attached to a strain-gage element that measured the force between the transducer and the fruit. The electronic unit comprised a high-power ultrasonic generator for activating and

Fig 1. Ultrasonic experimental arrangement: box A, electronic unit; box B, mechanical unit

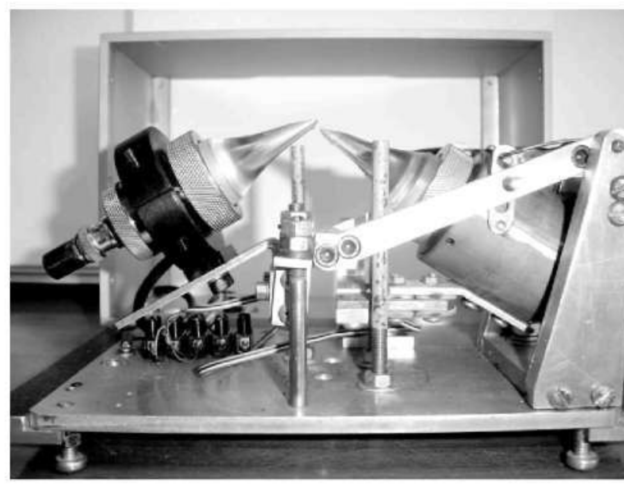

Fig 2. View of transducers and sensors assembly of the mechanical unit

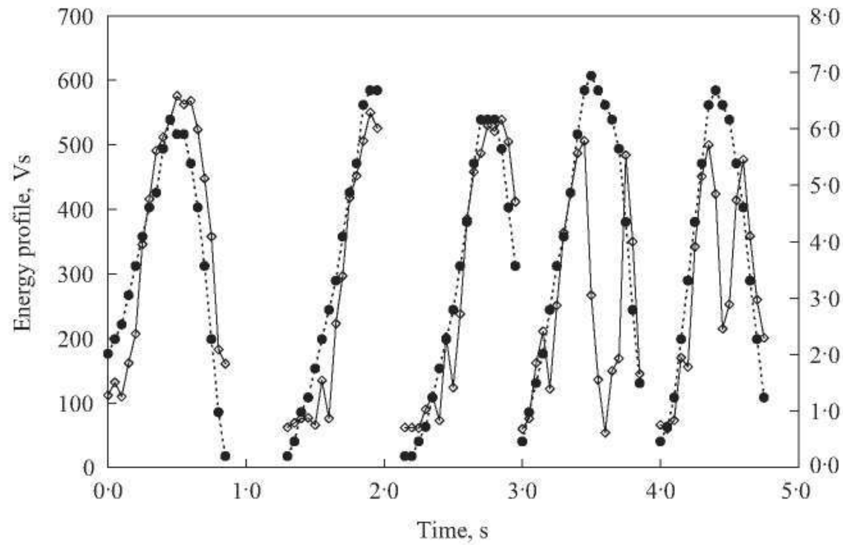

Fig 3. Force (···●···) and energy profile (—◇—) Versus time in discrete measurements (sample shown for green Jonagold apple)

monitoring the transducers, a strain-gauge controller, and a microprocessor unit that collected and processed the ultrasonic signals and strain-gauge readings, and sent the output to an external data acquisition system for further analysis (Mizrach *et al.*, 2003).

2.3. *Ultrasonic test procedures*

The ultrasonic measurements were performed on the red and on the green side of each fruit. The system was activated when a fruit was placed in contact with the transmitter and receiver tips, and a mechanical load was applied to them. Each fruit sample was tested under discrete manual loading increases (*Fig. 3*). The received ultrasonic energy and the mechanical loads applied to the fruit were measured simultaneously and recorded as series of data points at the rate of 20 Hz. To ensure synchronisation in capturing of ultrasonic data with load readings, each fruit was subjected to four to six loading cycles, each lasting 1 s, resulting in 20 data points per cycle with contact loads ranging from 0 to 9·53 N. Only the first successfully synchronised measurement was considered as an appropriate data point.

2.4. *Principles and instrumentation of destructive tests in confined compression*

A confined compression test was carried out with a Chatillon LRX testing machine and cylindrical probes (*Fig. 4*). The confined cylinder measured 17 mm in length and 17 mm in diameter, the cylindrical fruit sample was extracted from the outer part of the fruit

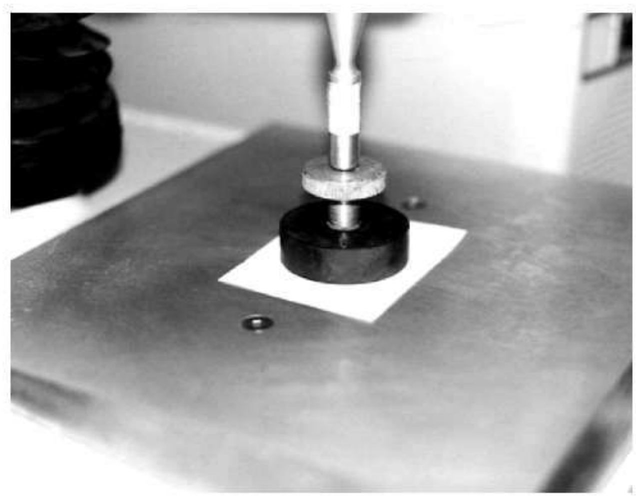

Fig. 4. A confined compression test device

tissue in the vicinity of the ultrasonic readings. The probes were confined in a hole of the same diameter as the fruit cylinder, in a disc of thickness equal to the probe height. Deformation was applied at 20 mm/min, to a maximum deformation of 2·5 mm. A 15·3 mm diameter rod was used as the probe, in order to avoid contact between the rod and the disc during compression. When maximum deformation was reached, the machine relaxed the deforming compression at the same rate in the opposite direction. One such test was performed on each fruit. The following data were recorded: maximum force at 2·5 mm deformation; force to deformation ratio (compression hardness) within the elastic regime; and juiciness, as expressed by the area of the juice spot that spread on a filter paper placed beneath the confining cell during the test. The measured data were combined in a computed texture degradation scale, ranging from 0 to 11 in which 0–3 was considered as fresh, 3–6 as ripe, and 6–11 as overripe (Barreiro *et al.*, 1998).

2.5. *Data analysis*

A program was implemented in Matlab software (1995); it processed the ultrasonic energy records and the applied force data obtained by the discrete loading method for each fruit sample. The energy profile and force applied were correlated to yield linear equations for each apple, each side, and each cultivar. The gradient (slope) in each equation was designated as the calculated value of the mealiness of the sample. The average correlation was found to be $R^2 = 0{\cdot}69$ for all fruits (Mizrach *et al.*, 2003). The linear analysis between energy profile and force applied was described in details previously (Mizrach *et al.*, 2003).

Data were subjected to analysis of variance (ANOVA), to multivariate analysis of variance (MANOVA), to Student's t-test, with level of significance α of 0·05, and to linear discriminant analysis.

3. Results and discussion

According to the destructive tests in confined compression method, out of the 120 fruits (comprising 60 of each of the two cultivars), 88 fruits were considered as fresh, 22 as ripe, and 10 as overripe. The classification of mealiness, as determined by the destructive test, was designated as a reference for the degree of mealiness and was compared with the results of the ultrasonic measurements. Table 1 summarises the results of the ultrasonic measurements for Jonagold and Cox apples, as obtained from the samples.

Not all of the fruits prepared for this study were successfully measured with the ultrasonic device. Some of the fruits could not provide ultrasonic readings and therefore, the total number of fruits listed in the table is less than the initially prepared 120.

In Jonagold apples, the average energy to force ratio (slope) for the green side was higher than that for the red side, for all mealiness groups. On the green side of the Jonagold apples, the values for overripe fruits were higher than those for fresh ones, whereas on the red side the values for fresh and overripe apples were alike. The results obtained for Jonagold apples did not correlate well with the mealiness levels; the differences were found to be minor and statistically insignificant, therefore, the results obtained for Jonagold apples by this method were not considered in the analysis.

In Cox apples, the slopes for fresh and ripe apples were alike, which implies that the resolution provided by ultrasonic measurements might be insufficient to distinguish between fresh and ripe fruits in terms of mealiness. Therefore, a comparison was made only between fresh and overripe mealiness groups.

Figure 5 shows the average slopes on Cox apples. For the red side measurements, the average slope obtained with the overripe group was 1·88 times as steep as that of the fresh group, and the difference was statistically significant ($\alpha = 0{\cdot}05$). For the green side measurements, the average slope obtained with the overripe group was 56% steeper than that of the fresh group but the difference between the groups was insignificant.

Table 1
Average results for energy to force ratio (slope), obtained from the measurements in Jonagold and Cox apples

		Energy to force ratio, V_s/N					
		Green			*Red*		
Variety		*Fresh*	*Ripe*	*Overripe*	*Fresh*	*Ripe*	*Overripe*
Jonagold	n[a]	27	8	4	30	8	4
	Av.	18·95	22·48	25·32	14·22	20·92	12·77
	S.D.[b]	13·52	18·16	13·36	9·58	18·59	8·92
Cox	n[a]	29	6	4	25	8	3
	Av.	17·21	17·01	26·79	20·95	18·82	39·50
	S.D.[b]	10·54	5·43	18·80	13·54	15·42	14·05

[a] *n, number of fruits.*
[b] *S.D., standard deviation.*

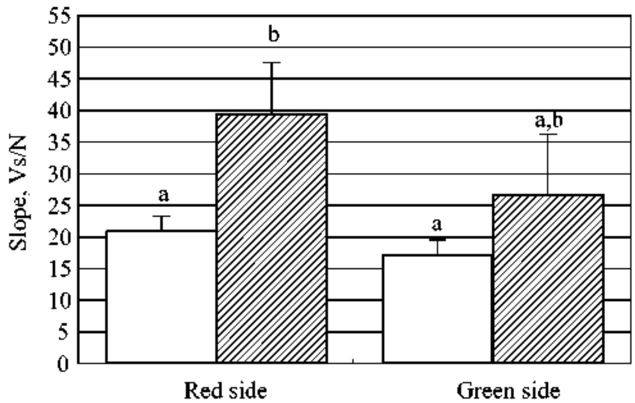

Fig 5. Average slopes on the red and green sides for different mealiness levels, as determined by the destructive tests in Cox apple; the different letters represent 95% significance of difference; the error bars represent the standard error: ■, *fresh;* ▨, *overripe*

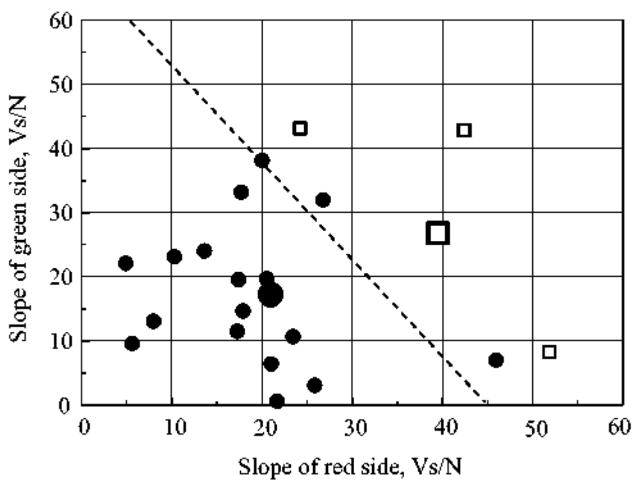

Fig 6. Red-green coordination system for Cox apples: •, *fresh apples;* ●, *average of the fresh group;* □, *overripe apples;* ☐, *average of the ripe group;* ----, *decision boundary line between the fresh and overripe apples based on the linear discriminant analysis*

In order to classify the mealiness level of each individual fruit, 20 apples that were successfully measured on both, red and green sides for the same fruit were taken. Multivariate analysis of variance (MANOVA) was performed on the red and green side parameters. It was found that the difference between the fresh and overripe groups that were classified by the confined-compression tests was statistically significant ($\alpha = 0{\cdot}05$). In addition, the significant difference between the mealiness groups, revealed good matching between the classifications, determined by the ultrasonic measurements and the confined-compression tests.

Figure 6 presents the results obtained from the classified Cox apples in a red-green coordination system *i.e.* red-side slope values plotted against green-side slope values.

The fresh apples are located in the lower left area of the graph, and the overripe apples are in the upper and right areas, where at least one coordinate value is high. The distance (vector magnitude) between the origin of axes to the average point of the overripe group is higher by 76% than of the fresh group. A linear discriminant analysis was performed on the results, revealed that the misclassification error rate was 5·8% and that the decision boundary equation between the fresh and overripe groups in *Fig. 6* found to be:

$$y = -1{\cdot}55x + 69{\cdot}3 \qquad (1)$$

where x and y are the slopes of the red-side and green-side, respectively, in V_s/N.

4. Conclusions

A system based on ultrasonic energy absorption technique was evaluated as a possible means for rapid non-destructive measurement of mealiness in intact apples. Ultrasonic energy transmitted through the fruit tissue and the load applied on the transducers was simultaneously measured. Linear equations were calculated between the ultrasonic energy and the load applied for each colour side of each apple. The slope of the linear plot of each equation was extracted as a measure of the mealiness of the sample.

The comparison between the results of the ultrasound measurements and the confined-compression tests showed good matching (probability $\alpha = 0{\cdot}05$) with the slopes for the fresh and the overripe mealiness levels for Cox apples (*e.g.* for measurements on the red side, the average slope for overripe fruits was higher by 88% than that for fresh fruits). The ultrasound results obtained for Jonagold apples did not correlate well with the mealiness levels; the differences were found to be minor and statistically insignificant.

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