Acoustic Measurement of Avocado Firmness During Low Temperature Storage: Effect of Storage Temperature

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Abstract
Accurate methods to assess avocado firmness are key tools to assess logistic alternatives for avocado exports. Traditional destructive tests do not allow continuous monitoring of the fruit during cold storage; however, the influence of storage conditions on the firmness of the product over time is significant. The present paper discusses the results found during the continuous monitoring of the acoustic firmness index of five groups of avocado ‘Hass’, stored at different ambient temperatures.

The results indicate that acoustic measurements may be more appropriate for fruit that has entered the ripening process than for unripe, fully green fruit. The variability of the fruit had the most significant impact on the mean acoustic firmness index, followed by the variation introduced by the storage time and, lastly, the variation due to the storage temperature. The use of mean acoustic firmness indices representing the average results for different fruits that have been treated under a particular set of storage conditions can potentially mask the true effect of the storage conditions. To avoid this problem, the selection of a “representative” firmness decay curve for a single fruit and for each set of conditions is recommended.

INTRODUCTION
World production of avocados (Persea americana Mill) was 1.4 million tons during 2001, with an estimated value of US$1,820 m. Australian production of avocado contributed 2.2% to the world production, with Australian exports amounting to 1.3% of the total national production in 2001.

Long transit times and short shelf life represent a significant obstacle for avocado exporters. To reach European markets, Australian avocados have to withstand shipping transit times of 33 to 44 days to the UK/Europe (Langdon, 2002). Additionally, avocados have to arrive with a shelf life suitable for a successful integration into the buyer's marketing chain. As new logistical solutions arise to overcome time constraints, a deeper understanding of the effect of cold chain conditions on the avocado quality is necessary. Accurate equipment and methods to assess firmness are key tools to aid such understanding.

General sources of information regarding cold storage of unripe avocado ‘Hass’ recommend a storage temperature of 5 to 7 ºC for early season fruit and 4 to 5.5 ºC for late season fruit (Woolf et al, 2002). After 3 to 4 weeks storage at those temperatures, fruit quality decreases. For Australian avocados, Zauberman and Jobin-Décor (1995) found a maximum storage life of 3 and 2 weeks for storage temperatures of 5 ºC and 8 ºC, respectively. Avocado stored at 2 ºC for 5 weeks did not show apparent negative effects. Jessup (1991) found that storage at 1 ºC for 30 days led to fruit of acceptable quality.

The evaluation of firmness in the aforementioned experiments was performed using destructive methods. Thus, the firmness evaluation was performed using different fruits and no continuous monitoring was possible. Mizrach (2000) investigated the use of a non-destructive ultrasonic technique to determine the ripening process of avocado ‘Ettinger’, held at five storage temperatures during 4 weeks. During the measurements, the fruit had to be warmed up to ambient temperature, thus disrupting the natural ripening process of the fruit to a certain extent. The method successfully monitored changes in avocado firmness during storage; the effect of the repetitive warming of product during
measurements and the variability of the fruit while averaging the results for each storage condition were not discussed.

Acoustic methods have been used for assessing firmness in horticultural products. Acoustic measurements are based on the analysis of the natural resonance frequencies produced when the fruit surface is tapped. A Fourier transformation on the signal allows the obtention of a firmness index, as described by Eq. (1):

$$ S = \frac{f^2 m^{2/3}}{2} $$

Where $f$ is the second resonance frequency (s$^{-2}$) detected in a vibration test and $m$ is the mass of the product (kg). The resulting firmness index ($S$) is a measure of the elasticity of the product. More detail on the principles of acoustic measurements can be found in Chen (1992) and Schotte et al (1999).

The two most commonly used methods to measure the acoustic response are the microphone-based and the piezoelectric-based systems. Galili et al (1998) investigated the acoustic response of ‘Fuerte’ and ‘Hass’ avocados, held at 22 °C and about 50% relative humidity during 9 and 6 days, respectively. The equipment used was a piezoelectric-based system. For avocado ‘Hass’, the authors found a low correlation coefficient between the firmness found using standard penetration tests and the acoustic firmness indices. They also found that the resonance frequencies and the firmness index could be clearly identified and these decreased steadily with respect to storage time, even though the theory of the acoustic firmness index was developed for products with a semi-spherical shape. To this author’s knowledge, no further work related to the measurement of firmness for avocado ‘Hass’ with an acoustic system has been published.

The aim of this paper is to present the results found during the continuous monitoring of the acoustic firmness index of five groups of avocado ‘Hass’, stored at different ambient temperatures. Empirical equations to describe the loss of firmness with respect to time for each storage temperature were developed. The acoustic firmness response was compared with the firmness (N), obtained with a mechanical device based on the Magness-Taylor principle. Finally, the effect of fruit variability, storage temperature and storage time on the acoustic response was assessed.

**MATERIALS AND METHODS**

Twenty-four open-top trays of unripe, late-season avocado ‘Hass’ (size 28) were collected from a coldstore at Flemington Markets (Sydney), after being transported in a refrigerated truck from a packing house in Nambour (Queensland). The fruit had not been previously treated with ethylene. The boxes were immediately transported to the Food Science Australia laboratories at North Ryde.

On arrival, the firmness of all the avocado groups was assessed using the Acoustic Firmness Sensor (AFS AWETA™, The Netherlands). The schematics of this system are presented in Fig. 1.

The acoustic testing was performed at 3 measurement points along the equatorial line. Immediately after, 20 avocados, randomly selected from 20 boxes, were subjected to a destructive penetration test, using a QuickMeasure Penetrometer System™ (HortPlus, Cambridge, New Zealand), with an electronic load cell and a hemispherical tip of 8 mm diameter. The fruit was unpeeled at three points along the equatorial line and punctured in a radial direction.

The remaining fruit was separated into 5 groups: 4 groups of 138 avocados each (stored at coldstores with temperature setpoints of 1 °C, 3 °C, 6 °C and 8 °C respectively) and one group of 100 avocados stored at 20 °C. Each tray was instrumented with a Tinytag™ temperature datalogger (12-bit internal sensor, range –40 to +85 °C, ± 0.2 °C, Gemini Data Loggers, UK). Additionally, two Tinytag™ relative humidity dataloggers (8 Bit internal sensor, range 0 to 95%, ±3%, Gemini Data Loggers, UK) were placed into each coldstore.
All fruits were subjected to an acoustic testing twice per week. On each of these occasions, two or three specimens of each group were selected for the destructive firmness test. The experiment was continued until the majority of the product stored was ripe, as determined by both the skin colour and the firmness of the product.

RESULTS AND DISCUSSION

Even though the temperature setpoint values of 1 °C, 3 °C, 6 °C, 8 °C and 20 °C were used to control the air temperature during storage, the product temperatures monitored differed from the air temperature setpoint as presented in Table 1. The most significant factor affecting product temperature was the duration of the defrost system in the particular coldstores used. For practical purposes, the groups in the discussion of the results are still identified by the temperature setpoint. However, these values were corrected in the calculations performed to assess the effect of storage temperature on the acoustic response.

Firmness of avocados on arrival

The initial firmness of the product exceeded the capacity of the load cell in the penetrometer used (208.9 N). For comparison purposes, it was assumed that this value represented the initial product firmness.

The results of the initial acoustic measurement of the 652 avocados distributed in the five temperature groups showed that 82% of the total number of avocados tested had an initial firmness index within 25 to 50x10^4kg^2/3s^-2. This indicated that either high firmness variability was present within the avocados, or that the AFS system was not able to differentiate adequately between products, due to the high firmness levels.

Firmness of avocados during coldstorage

Figures 2 and 3 show the average firmness with respect to storage time, as measured with the AFS system and the penetrometer, respectively. For product stored at 3 °C, both methods did not detect changes in firmness occurring before Day 30 (in the case of the AFS system) and before Day 40 (in the case of the penetrometer). The acoustic response for product subjected to a 1 °C temperature did not vary significantly during the whole storage period. These results and previous unpublished experimental trials suggest that the acoustic measurements may be more appropriate for avocado that has entered the ripening process than for unripe, fully green fruit.

Table 2 presents the results from a least square fit, performed to obtain empirical correlations between the acoustic firmness index and the storage time for each temperature tested. Data before the Day 30 threshold mentioned before was excluded in these calculations and only data from Day 31 onwards was used. For the avocados stored at 20 °C, the best model describing the relationship between the abovementioned factors was a power model; however, for the avocados stored at 3 °C, 6 °C and 8 °C, the best fit was obtained using an exponential model. The latter relationship was also found by Galili et al (1998), for avocado stored at 22 °C. For product stored at 1 °C, changes in firmness respect to storage time were small and no correlation was found in the 66 days of storage.

The correlation between the responses of the AFS system and the Magness-Taylor method was calculated, using only data of less than 60 N to overcome the uncertainty observed in the high firmness levels in both methods. The poor correlation found (r^2=0.06) was consistent with the observations of Abbott and Harker (2002), who established that modulus or elasticity values obtained from resonance frequency data correlate well with firmness values measured using compression test, but do not correlate well with Magness-Taylor forces.

Figure 4 presents a comparison of the effect of the natural variability of the fruits, the storage temperatures and the storage time on the acoustic firmness index. This plot represents averages of data from 10 fruits from each temperature group (except the 20 °C group), during the initial 45 days of storage. The results indicate that the variability of the fruit had the most significant impact on the acoustic firmness index, followed by the...
variation introduced by the storage time and, lastly, the variation due to the storage temperature. Hence, though the AFS system is able to discriminate the change of firmness with respect to storage time, the statistical noise introduced by the variability between fruits is still significant. The selection of a “representative” firmness decay curve for a single fruit (e.g. a firmness curve that does not represent the extremes in a group of curves) and for each set of conditions would avoid the introduction of uncertainty due to the natural product variability.

CONCLUSIONS
For product stored at 3 °C, both destructive and non-destructive methods did not detect changes in firmness occurring before Day 40 and Day 30, respectively. The acoustic response for product stored at 1 °C did not vary significantly during the whole storage period. These results indicate that the acoustic measurements may be more appropriate for avocado that has entered the ripening process than for unripe, fully green fruit.

The best model describing the relationship between the acoustic firmness index and the storage time for avocado stored at 20 °C was a power model; however, for avocados stored at 3 °C, 6 °C and 8 °C, the best fit was obtained using an exponential model.

A poor correlation was found between the acoustic firmness index and the results from the Magness-Taylor puncture tests. These results are congruent with previous published research.

The variability of the fruit had the most significant impact on the mean acoustic firmness index, followed by the variation introduced by the storage time and, lastly, the variation due to the storage temperature. One of the main advantages for using acoustic methods is that a single fruit can be monitored, thus decreasing the effect of product variability. However, the use of mean acoustic firmness indices, representing the average firmness of different fruits that have been treated under a particular set of storage conditions, can mask the true effect of storage temperature, time and others. The selection of a “representative” firmness decay curve for a single fruit and for each set of conditions may overcome this problem.

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Literature Cited


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Tables

Table 1. Air setpoint temperature, actual product temperature averaged during coldstorage and duration of coldstorage.

<table>
<thead>
<tr>
<th>Setpoint temperature (°C)</th>
<th>Average product temperature during coldstorage (°C)</th>
<th>Duration of coldstorage (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.8</td>
<td>65</td>
</tr>
<tr>
<td>3</td>
<td>2.4</td>
<td>65</td>
</tr>
<tr>
<td>6</td>
<td>5.8</td>
<td>65</td>
</tr>
<tr>
<td>8</td>
<td>8.5</td>
<td>47</td>
</tr>
<tr>
<td>20</td>
<td>20.8</td>
<td>16</td>
</tr>
</tbody>
</table>

Table 2. Empirical correlations between the acoustic firmness index with the storage time for each temperature tested, where $S =$ Acoustic firmness index ($10^4$kg$^{2/3}$s$^{-2}$) and $D=$Storage time (days).

<table>
<thead>
<tr>
<th>Setpoint temperature (°C)</th>
<th>Empirical equation</th>
<th>Correlation coefficient</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>No equation obtained</td>
<td>-----</td>
</tr>
<tr>
<td>3</td>
<td>$S=36.218<em>e^{-0.00898</em>D}$</td>
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<tr>
<td>6</td>
<td>$S=29.549<em>e^{-0.0149</em>D}$</td>
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<tr>
<td>8</td>
<td>$S=28.277<em>e^{-0.025</em>D}$</td>
<td>0.8741</td>
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<tr>
<td>20</td>
<td>$S=47.082*D^{-0.7894}$</td>
<td>0.9946</td>
</tr>
</tbody>
</table>
Figures

Fig. 1. Schematics of the acoustic device AWETA™ used for measuring the acoustic firmness index.

Fig. 2. Variation of mean acoustic firmness index with storage time at five storage temperatures for avocado ‘Hass’. ■, 1 °C; ●, 3 °C; ▲, 6 °C; ▼, 8 °C; ◆, 20 °C.
Fig. 3. Variation of mean firmness with storage time at five storage temperatures for avocado ‘Hass’. ■, 1 °C; ●, 3 °C; ▲, 6 °C; ▼, 8 °C; ◇, 20 °C.

Fig. 4. Comparison of the effect of the natural variability of the fruits, the storage temperatures and the storage time on the acoustic firmness index. This plot represents data from 10 fruits from each temperature group (except the 20 °C group), during the initial 45 days of storage. The dots ● represent the mean response for each factor level.