Internal characteristics visualization of fresh agricultural products using traditional and ultrafast electron beam x-ray Computed Tomography (CT) imaging

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Abstract
Fresh fruits, vegetables and nuts represent a large, highly important, and growing industry. Nonetheless, little is known about their in vivo characterization and morphology, the effect of mechanical harvesting, peelability, postharvest mold, physiological decay, and internal quality.

Currently, destructive techniques can be employed to evaluate samples for internal product attributes. However, clearly not all produce can be evaluated. Thus, there is a need to develop a nondestructive technique able to assess fresh agricultural commodity internal components, especially disorders. In this study, medical grade computed tomography (CT) was used to obtain transversal two-dimensional (2D) images from several fresh agricultural product phenomena. Phenomena included the internal decay of chestnuts (Castanea spp.), internal defects in pickling cucumbers (Cucumis sativus), translucency disorder in pineapples (Ananas comosus), pit presence in sweet (Prunus avium) and tart cherries (Prunus cerasus var. Montmorency), and plum curculio (Conotrachelus nenuphar) infestation of tart cherries. In addition, ultrafast limited-angle-type x-ray CT scanner was also used to visualize internal characteristics of fresh chestnuts. The 2D CT x-ray images and postprocessing three-dimensional CT image reconstruction indicate that CT can be used as an accurate in vivo insight of fresh intact agricultural products.

Results suggest potential for nondestructive in-line sorting of the internal quality of several agricultural products. The long-term objective is that the fresh product industry will then be able to detect internal quality attributes of fresh agricultural commodities, at a relatively early stage, after validation under commercial conditions.

Key words: Postharvest, quality, noninvasive, defect detection, fresh products.

1. Introduction
It is estimated that a total of about 500 million metric tons of fresh fruits, vegetables and nuts are produced annually in the world, representing a large, highly important, and growing industry (FAO, 2010). At the moment, approximately 25 to 30 % of the total production is discarded after harvest, mainly because of undetectable internal quality, safety issues, and senescence (Kader, 2002). This represents large product and economic losses, which disturbs agriculture industry sustainability and its ability to consistently offer healthy, safe, and good quality produce.

Fresh and processed agricultural commodity quality is measured not only by external factors such as color, shape, size, surface blemish, and surface mold, but also by internal disorders and freshness, which are very important for consumer acceptance. Most importantly, the external appearance usually is not altered, at least initially, by internal disorders making them difficult to detect without destructive evaluation. Internal disorders usually are the result of
anatomical and physiological changes within the tissue such as moisture loss, chemical conversion, discoloration, senescence, microorganism attack, cell breakdown (physiological decay), foreign object presence, and insect injury (Upchurch et al., 1993).

In some cases, these problems can lead to a completely unmarketable product. Additionally, negative response from consumers can jeopardize the marketing of fresh produce causing severe economic losses. Because of the lack of in vivo diagnostic tools, little is known about how and when cell breakdown progresses and microorganisms infest fresh agricultural products. Moreover, very little is known about pre- and post-harvest handling strategies that negatively or positively affect the quality and internal components of fresh and processed agricultural products. This includes, the effect of mechanical harvesting, pre-harvest treatments (Mandujano et al., 1998; Sieber et al., 2007), peelability (Guyer et al., 2005), optimum storage conditions, quality measurement and standards (Mencarelli, 2001), as well as fresh chestnut in vivo fruit morphology for cultivar characterization (Ertan, 2007).

Currently, destructive techniques can be employed to evaluate internal quality attributes, characteristics, and components. However, this is not an in vivo technique and while trying to determine quality, not all commodities can be evaluated (Butz et al., 2005; Donis-Gonzalez et al., 2010). In recent years, techniques based on two-dimensional (2D) X-ray, and computed tomographic (CT) imaging have been explored, and are used for non-destructive determination of internal characteristics of a variety of agricultural and food products (Abbott, 1999; Haff, 2008). Despite considerable research effort, in vivo component characterization and real-time inspection systems of internal quality of fresh produce, are still uncommon in the industry, mainly because of limitations in useful information when using high-speed systems (Butz et al., 2005). However, because of recent advances in high-performance computers, new detector technologies, accessibility, high-performance x-ray tubes, real-time imaging, cost diminution, and significant decrease in image acquisition time, the field of non-medical CT applications and in-line CT sorting systems are gaining tremendous attraction (Hanke et al., 2008).

X-ray is short wave radiation (aprox. 0.01 – 10 nm) with high energy (1.92 x 10^{-17} – 1.92 x 10^{-14} J) that can easily penetrate matter. Traditional CT is an imaging procedure where an x-ray tube is rotated around an object or objects and the attenuation is recorded on a detector (Fig. 1a). Other equipment may contain a rotating stage in front of a fixed x-ray tube and detector.

Alternatively, newer and ultrafast techniques exist and are being further developed for potential fast in-line imaging. Fig. 1b and Fig. 1c show the working principle and scanning geometry of the ultrafast Rossendorf electron beam x-ray tomograph (ROFEX) scanner. An electron beam of sufficient energy is produced by an electron beam gun, focused onto a semicircular x-ray production target, which surrounds the test section. The electron beam is swept rapidly across the target by means of an electromagnetic deflection system and that way x-rays are generated from a moving focal spot. Radiation passes the object of investigation and is attenuated regarding Lambert’s law. Radiation intensity signals are recorded by a fast x-ray detector. The detector is designed as a circular ring and mounted stationary inside the scanner head with some axial distance to the plane of the focal spot path. From sets of projection data acquired from 240 degrees, superimposed cross sectional images can be reconstructed using a conventional filtered back projection algorithm. The scanner is optimized with respect to ultrafast imaging, which implies a small source-detector separation and shorter electron path, accordingly. Objects with a diameter up to 80 mm can be scanned without any limited angle artifacts (Fischer et al., 2008).
FIGURE 1: (a) GE (GE Healthcare, Buckinghamshire, England, Great Britain) BrightSpeed™ RT 16 Elite computer tomography (CT) scanner. (b) Ultrafast Rossendorf electron beam x-ray tomograph (ROFEX) scanner working principle, and (c) cross-section scanning geometry. (d) Experimental setup at the ROFEX-scanner

There are several advantages of CT compared to traditional 2D X-ray imaging. First, CT completely eliminates the superimposition of images of structures within the samples and outside the region of interest. The reason is because in 2D X-ray imaging, only one projection image (X-ray transmission through sample) is acquired per sample, while in CT a transverse 2D-image or slice is reconstructed using information from more than one 2D projection image, acquired at different angles. Second, data from one CT imaging procedure can be reconditioned to be observed in various planes, known as multi-planar imaging; or even observed volumetrically by creating a three-dimensional (3D) image, merging the information from all 2D slices.

CT methods for accurate visualization, segmentation and inner component identification of fresh agricultural commodities, which include the internal decay of chestnuts (Castanea spp.), internal defects in pickling cucumbers (Cucumis sativus), translucency disorder in pineapples (Ananas comosus), pit presence in sweet (Prunus avium) and tart cherries (Prunus cerasus var. Montmorency), and plum curculio (Conotrachelus nenuphar) infestation of tart cherries, are not available. We hypothesize, that CT scanning can be used as an in vivo tool to accurately visualize the internal attributes of these fresh agricultural products. For that reason, the objective of this study is to scan these fresh agricultural products, using a traditional and an ultrafast CT scanner to evaluate if internal attributes of agricultural commodities can be visualized.

2. Materials and methods

2.1. In vivo CT imaging scans and visualization

Samples (chestnut, pickling cucumbers, pineapples, sweet and tart cherries) CT scans were performed on a GE BrightSpeed™ RT 16 Elite, multi-detector CT instrument (General Electric Healthcare, Buckinghamshire, United Kingdom), located in the Department of Small Animal Clinical Sciences at Michigan State University. Scanning parameters and CT equipment specifications can be found in Table 1. CT scanning was performed by placing and securing numbered samples onto a whole polyethylene sheet, placed on the CT scanner table, as exemplified in Fig. 1a. Acquired images are stored as a set of 2D images. Thereafter, from a single acquired data set, 2D images were reconstructed into 3D images, using the Osirix Imaging Software V3.6.1 (http://www.osirix-viewer.com/).
TABLE 1: Scanning parameters for the CT – General Electric, BrightSpeed™ RT 16 Elite

<table>
<thead>
<tr>
<th>Parameter (Units)</th>
<th>Chestnuts, cucumbers, and cherries</th>
<th>Pinneaples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage (keV)</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Current (mA)</td>
<td>170</td>
<td>240</td>
</tr>
<tr>
<td>Slice thickness (mm)</td>
<td>0.625</td>
<td>10</td>
</tr>
<tr>
<td>Pixel area (mm²)</td>
<td>0.601</td>
<td>0.601</td>
</tr>
<tr>
<td>Voxel volume (mm³)</td>
<td>0.376</td>
<td>6.0</td>
</tr>
<tr>
<td>Resolution in the trans-axial plane (X-Y) (pixels/mm)</td>
<td>1.289</td>
<td>1.289</td>
</tr>
<tr>
<td>Pitch (table movement – mm : rotation)</td>
<td>17.5:1</td>
<td>17.5:1</td>
</tr>
<tr>
<td>Scan time (s) per sample</td>
<td>0.6 - 1</td>
<td>3</td>
</tr>
</tbody>
</table>

In addition, a different set of chestnut samples were scanned using the ultrafast ROFEX-scanner. This scanner was operated at 150 keV maximum x-ray energy with a maximum electron beam power of 10 kW. The system provides a temporal resolution of up to 7000 frames/s at a spatial resolution of roughly 1 mm, depending on attenuation behavior of the object. Chestnuts were labeled (numbered) and packed in a thin plastic hose. The hose was pulled through the scanning plane using a stepper motor, at a constant speed of 1 m/s, as seen in Fig. 1d. From this, sets of cross sectional 2D CT images for every chestnut were acquired. The frame rate was chosen to 2000 frames/s, which is a good compromise between image quality and temporal resolution.

2.2. Visual based fresh product quality assessment

After CT scanning, each fresh product was transversely sliced in 4 sections using a sharp hand knife. Slice sizes varied depending on product size, but typically were between 5 to 7.5-mm thickness for small commodities like chestnuts, and 40 to 60.5-mm thickness for larger commodities like pineapples. Internal faces between each slice (total of 6), from each agricultural commodity, were then qualitatively/visually assessed for specific quality aspects, previously mentioned in the introduction section.

3. Results and discussion

Fig. 2 includes an example of cross-sectional 2D CT images of uncut fresh chestnuts (Fig. 2a), sweet and tart cherries (Fig. 2b), cucumbers (Fig. 2c), and pineapples (Fig. 2d). In these images, healthy and rotten chestnuts, pit and insect damaged cherries, physiologically affected pickling cucumbers, and translucent pineapples can be viewed. Parallel, in the case of Fig. 2a and Fig. 2d, color images of fresh slices, which correspond to approximately the same CT scanned slices, can also be observed. Fig. 2 includes a 3D CT image reconstruction of samples, rendered with different colors, which correspond to approximately the same CT scanned slices, can also be observed. Fig. 2 includes a 3D CT image reconstruction of samples, rendered with different colors, which correspond to approximately the same CT scanned slices, can also be observed. Fig. 2 offers preliminary results of what can be inferred about fresh produce quality, using the 2D and 3D CT images. Visually, using CT images, differences can be distinguish between healthy and rotten chestnuts, healthy cherries versus those containing pits or are damaged by insects, healthy and physiologically defective cucumbers, and translucent versus healthy pineapples. In certain cases (e.g. pineapple translucency), this approach/technology can perform a spatial analysis of a whole fruit, thus showing that if a pineapple is moderately translucent at the bottom, it might not be translucent on the top. Other pineapples might have an evenly distributed translucency level (i.e., moderate or extreme) through the fruit. These scenarios might have positive implications in processing, where half of the pineapple (e.g., non to moderate translucency level) could still be used, instead of discarding the whole fruit, as if it is completely translucent.
FIGURE 2: Color raw image slices, cross-sectional 2D CT images acquired using the GE BrightSpeed™ RT 16 Elite CT scanner, and 3D reconstruction of (a) chestnuts, (b) sweet and tart cherries, (c) cucumbers, and (d) pineapples.

This study showed that CT technology could be used as a novel technique that will be able to visualize macroscopic changes in fresh produce tissue (e.g. decay, translucency, and physiological defects), and presence of foreign objects (e.g. pits). In addition, the images presented in this study are essential for developing classification algorithms to sort fresh agricultural commodities based on their internal characteristics. Even though more research is required to develop a classification algorithm, it can be affirmed that these preliminary CT images can be used as a reference to determine the presence of internal quality attributes of fresh agricultural commodities. These results indicate that CT might be a useful technique to develop future prediction models of internal produce quality. Nonetheless, results infer, that in addition to raw images, other methods related to image processing, feature extraction, and pattern recognition, might be a requirement to aid the development of future sorting algorithms.

Fig. 3 offers preliminary results of what can be inferred about fresh quality using the ultrafast ROFEX CT-images. As it can be observed, from the CT images it is difficult to visually distinguish between extremely decayed (Fig. 3c) and healthy chestnuts (Fig. 3a). On the other hand, when decay tissue is embedded between healthy tissue (Fig. 3b), a slight difference in gray scale intensity values can be visually observed. Nonetheless, the presence of void spaces and pellicle were easily discerned. Our research group has concluded that the scanning conditions using the ROFEX scanner were not optimum to detect decay because the maximum x-ray energy of 150 keV was too high. Therefore, future research will focus on optimizing image quality using different scanning parameters; with the objective of rapidly and effectively detecting properties in different fresh agricultural produce, for example chestnut rot, known as decay.

FIGURE 3: Visual preliminary results of CT images obtained using the ROFEX-scanner. (a) Healthy, (b) partially decayed (rotten), and (c) completely decayed chestnuts. (d) 3D reconstruction of two chestnuts, showing a rotten section (white arrow).
4. Conclusions

The medical grade GE-CT imaging system provided 2D CT images of the internal structure, issues, and components of fresh agricultural commodities. Commodities included chestnuts, sweet and tart cherries, pickling cucumbers, and pineapples. In addition, an ultrafast limited-angle-type CT provided 2D CT images of the internal structure of fresh chestnuts. Furthermore, reconstructed 3D images, obtained by a set of 2D CT images, enable the spatial visualization of internal attributes of a whole fruit.

In future studies, sorting algorithm speed, equipment cost and characteristics, as well as other methods related to image processing, feature extraction and pattern recognition are considered in the development of CT sorting algorithms. More studies must be pursued to evaluate the accuracy of sorting algorithms and in-line classification. The main advantage of using CT images with the aid of other algorithms will be that CT is a fast, non-invasive procedure that has the potential to be adapted for quality evaluation and in vivo in-line sorting. In general, this study indicated that CT has a high potential for nondestructively visualizing internal quality attributes of fresh agricultural commodities.

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