Watercore in Apples: Causes, concerns, detection and sorting

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Watercore is a serious physiological disorder of apples that occurs on the tree. It is typified by water-soaked areas of the cortex, which cause the tissue to become translucent. In its mildest cases, watercore is localized near the primary vascular tissue running through the cortex (Fig. 1, upper left). The disorder is highly cultivar-dependent; however, watercore has been reported in most cultivars (Table 1). The symptoms can be radial in nature, often located near the vascular strands, or more coalesced in nature. These symptoms have been referred to "radial" and "block" watercore, respectively (Harker et al., 1999). In severe cases, it can encompass the entire core area of the fruit and result in liquid accumulation in the seed cavity (Fig. 1, upper right). In extreme cases, the water-soaked areas can even extend out to the surface of the fruit (Fig. 1, lower left) such that light passes readily through the cortex and skin (Fig. 1, lower right). Upon storage, watercore can dissipate, but in some cases, leads to the development if sometimes severe internal browning (Fig. 2).

Figure 1. Watercore. Internal injury can be mild or severe and can extend to the surface in severe cases, (lower right).

Figure 2. Internal injury caused by watercore following storage.

HISTORY

Watercore was, as far as has been determined, first described in published literature in 1886 by Paul Sorauer (Sorauer, 1886) in a German textbook entitled *Handbuch der Planzenkrankheiten*. Sorauer described the disorder as "glassy" flesh and called the disorder "glasige apfel". He described the watercore tissue as being distinctly sweeter, firmer, having less intercellular air, having less starch, browning quicker, and smelling differently than the unaffected tissue. When Soraur published this description, it was evident that the disorder was widely recognized, but had not been the subject of serious research. [Note: terms used to describe watercore over the years include *glasige apfel*, *pommes vitreuses*, *la vitrescenza delle mele*, *glassy disease of apple*, *apple glassy disease*, *glassy core*, *watery-nose*, *pineapple centers*, and *water core* (Marlow and Loescher, 1984)]. By 1934, the favored term became watercore, although, for reasons made obvious by the lower right-hand image in Fig. 1, it is termed glassiness when the symptoms are visible from outside the fruit.

Early work in the U.S. was broadly distributed across the land-grant experiment stations and in semi-private and federal laboratories. O'Gara (1914), a pathologist and entomologist from Medford, Oregon, published several papers on the causes of watercore. He concluded that watercore was promoted by several environmental and biological factors including good fruit exposure, excessive or vigorous growth, well-cultivated soils, excessive precipitation or irrigation, extremes in temperature and humidity, severe pruning just before ripening, low temperatures (especially frosts) prior to harvest, factors that induce the rapid conversion of starch to sugars.

PHYSIOLOGY

Watercore is caused by the accumulation of sorbitol-rich liquid in the intercellular spaces of the apple tissue. As the liquid accumulates between the cells of the fruit, it reduces the scattering of light passing through the tissue, causing it to be translucent. The disorder only develops on the tree. Detection technologies using light transmission can successfully identify affected fruit at the time of harvest. However, the symptoms disappear during storage even though damaged tissue remains (Harker et al., 1999; Upchurch and Throop, 1994).

The liquid causing watercore is rich in sorbitol, which is the primary transport carbohydrate of apple (Marlow and Loescher, 1985; Fig. 3). Current evidence points to the cause of watercore being related to the unloading of photosynthate-rich liquid from the phloem cells of the vascular tissue that runs through the apple fruit. Normal sorbitol metabolism is impaired, but that o sucrose is not. In symptomatic tissues, the sorbitol-rich liquid of the phloem is somehow inhibited from being absorbed by the cells in the fruit cortex (Gao, et al., 2005), leading to the accumulation of the 'sap' unloaded from the phloem cells and a reduction in reducing sugars (fructose and glucose) in the fruit cortex. In normal tissue, the cells of the apple cortex likely have an excess capacity to absorb the unloaded phloem cell sap.

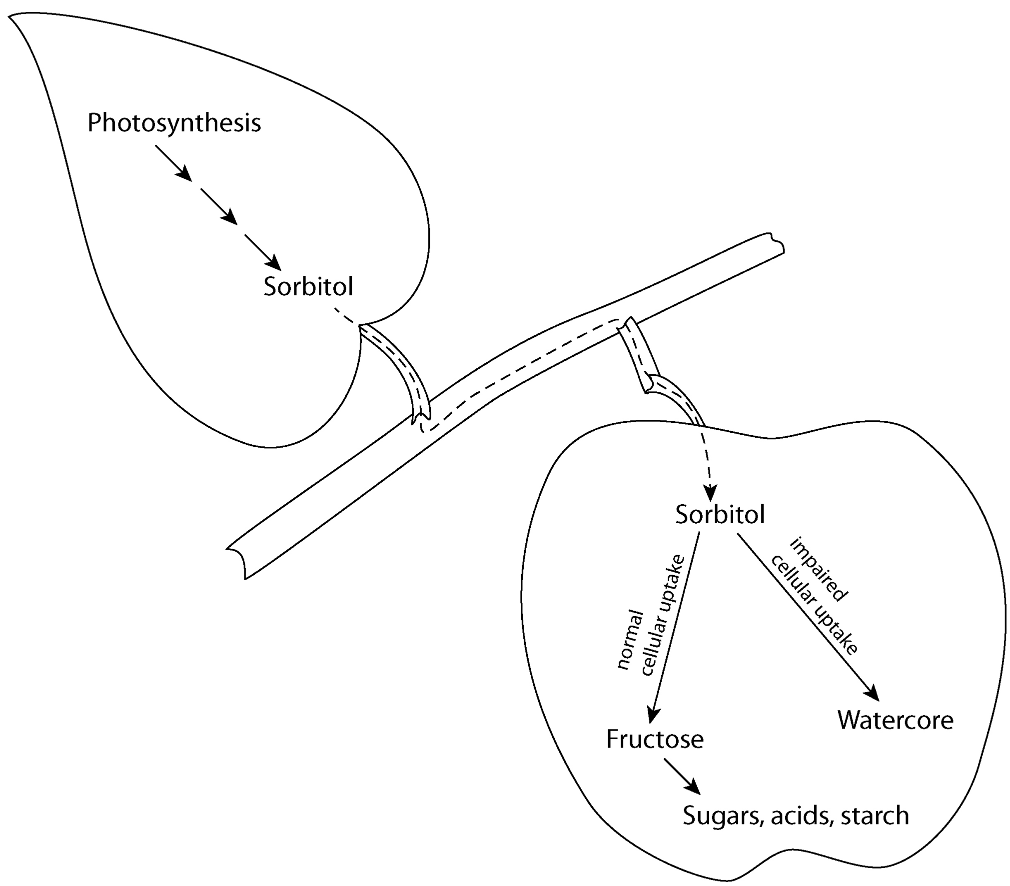

Figure 3. Route of sorbitol transport form source (leaf) to sink (fruit) and its contribution to watercore development (redrawn from Marlow and Loescher, 1984).

FACTORS AFFECTING WATERCORE

In their review, Marlow and Loescher (1984), summarize those factors historically linked to watercore development and evaluated their potential to be contributing factors. These include:

Water regime	Generally speaking, the amount of water available to the plant has not been shown to be a causative factor and is probably not linked. Excessive humidity around the fruit, however, may contribute to symptom development. A link between watercore development and late season rainfall has been attributed to the fact that rainfall delays harvesting, allowing the fruit to mature and become more prone to watercore development.
Temperature	High fruit temperatures are linked to watercore development, as are periods of low temperature (below 40 °F). The exposed side of the fruit, with higher day/night temperature fluctuations, may be more susceptible to disorder development. In that low temperatures can induce ripening in some varieties and that high temperatures drive more rapid fruit development, the effect of higher temperatures and/or low temperatures may be partly through induction of ripening and advancing the maturity of the fruit.
Mineral nutrition	High nitrogen levels have been linked to increased watercore incidence, but the relationship is not clear-cut. There is some indication that high nitrogen and low calcium may be important in watercore development, but conclusive data are lacking. Boron in excessive levels has been shown to induce watercore. This relationship may also be linked to fruit maturity in that boron at high levels can inhibit fruit drop and lead to advanced maturity of the fruit at the time of harvest. There appears to be a link between low calcium levels and watercore incidence, but the relationship is not strong. Interestingly, infiltration of fruit with calcium can inhibit symptoms. While calcium is known to have an impact on a number of processes in pome fruit, it's impact on slowing maturation of the fruit may be the most critical in the case of watercore development. Interestingly, the application of calcium may also impact watercore by influencing leaf senescence; slowing the aging process in leaves prevents the rapid export of sorbitol associated with the latter stages of life stages of leaves.
High source-to-sink ratio	A high source-to-sink ratio has been shown to have a marked impact of watercore development. Defoliation and girdling studies have shown that if the products of photosynthesis are in excess, as in the case of seasons with a short crop, the likelihood of watercore increases measurably. Linked to this, watercore has been found to be elevated in young trees bearing small crops, light crop loads or large-sized fruits, and excessive thinning. When the source-to-sink ratio is high, the fruit receives more photosynthate, allowing it to reach larger sizes and higher

levels of metabolites including acids and sugars. Furthermore, a high source-to-sink ratio can also accelerate maturation, which is associated with increased watercore incidence.

Maturation and ripening — While there are occasional references to watercore occurring in immature fruits (on the sunny side of the tree), the overwhelming evidence suggests that advanced maturity is a required feature for the development of watercore. Evidence also comes from the application of growth regulators that impact fruit ripening: ethylene applications enhance watercore and Alar (daminozide) diminishes watercore. The impact of maturation may be mediated through cell wall changes, loss in the integrity of cellular membranes, rapid breakdown of starch, and altered transport of photosynthate. Of these, the latter seems to have the greatest likelihood of being most directly associated with watercore development. Evidence suggests that when the tree produces elevated amounts of photosynthate (which is typically in the form of sorbitol) at a time when the capacity of the fruit cells to take up the sorbitol is diminishing (as it is during the latter stages of development), then the stage is set for symptom development.

POSTHARVEST CONSIDERATIONS

While watercore dissipates partially or even completely with storage, it tends to "weaken" fruit and make them more susceptible to degradation in storage and in the marketing chain. In addition, watercore makes fruit more susceptible to CO_2 injury (Park and Lee, 1991), probably due to a decrease in tissue permeability and the build-up of CO_2 and the induction of fermentation (Agenta et al., 2002). The low temperatures of storage slow the reabsorption of the free water between the plant cells and CA storage retards this process even further. It is thought that the effect of CA and low temperatures are through the inhibition of ripening (Marlow and Loescher, 1984). For this reason, there is some concern that 1-MCP may exacerbate the slowing of watercore dissipation even further. In one study, the ripening inhibitor 1-MCP has been reported to have no effect on dissipation of the symptoms of watercore in storage (Argenta et al., 2005), but other sources suggest the relationship is more complicated and 1-MCP may indeed slow dissipation and lead to greater internal browning in some cases (Watkins, 2007).

A scale has been developed for the purpose of judging the severity of watercore in fruit lots in order to determine whether the fruit should be sheld for short or long-term storage (Neuwald et al., 2010, Fig. 4). Slight water (0-2 on the six-point scale) was deemed "acceptable" and would be non-injurious in short- to medium-term storage.

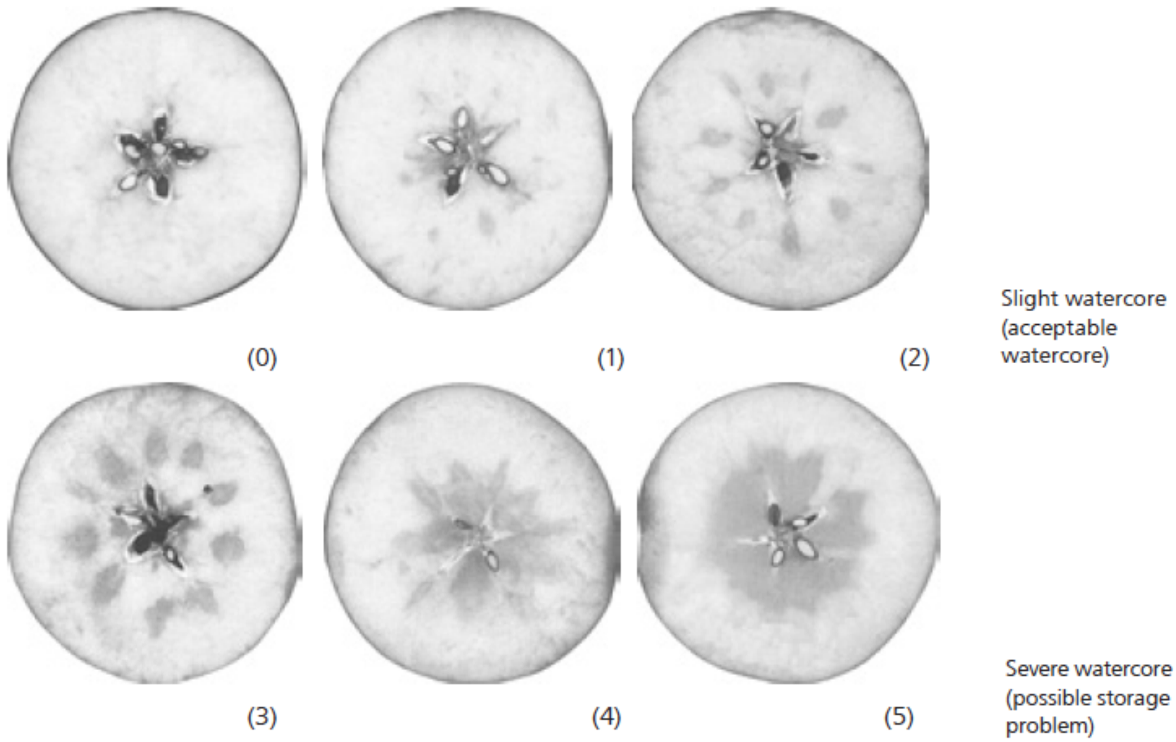

Figure 4. Reference images for scoring watercore severity on a range of 0 to 5 (o represents fruit without watercore and 5 is equivalent to 40% or more of flesh involvement.

DETECTION AND SORTING

Detection of watercore is possible using a number of techniques. Non-destructive detection techniques include light transmission, fruit density, nuclear magnetic resonance (NMR), X-ray computed tomography (X-ray CT), and thermography.

One method is detection and sorting based on the density of the fruit (Cavalieri et al., 1998). Fruit with watercore have a greater density (a.k.a. specific gravity) than fruit without watercore. The density of non-affected fruit typically ranges between 70% and 85% of the density of water, but the density of watercore-containing fruit is higher, between 90% and 95% that of water. This observation has lead to a simple means of detection and separation; fruit can be separated efficiently using a liquid of appropriate density - usually about 90% the density of water. This can be managed using chemical additives (typically alcohol) having a low density or using aeration (Fig. 5). In one method, fine air bubbles are introduced into the dump tank using a sparger and the reduced water density causes the watercore-affected fruit to sink below a sorting plenum and the unaffected fruit float above the plenum and are thereby separated. The problem with this technique is that fruit density varies from orchard to orchard and is a function of variety and fruit size, with larger fruit typically being less dense.

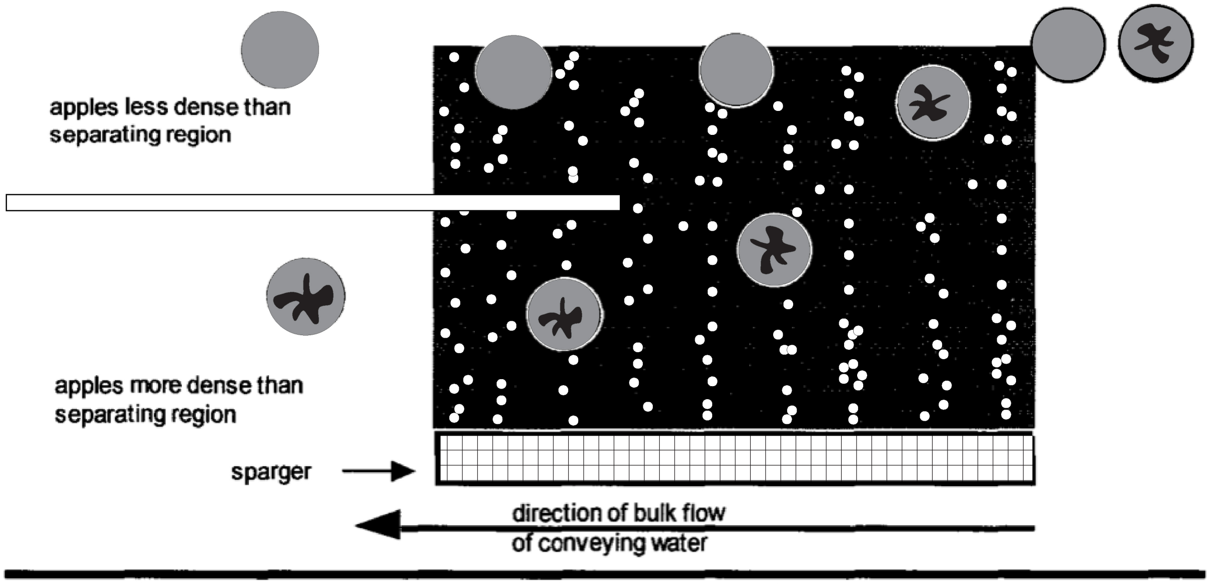

Figure 5. Schematic depicting the separation of less dense, non-watercore apples (upper stream of fruit - gray spheres) from more dense, watercore-containing fruit 9lower fruit stream) (redrawn from Cavalieri et al., 1998).

Use of light transmission through the fruit was an early method to detect watercore (Olsen et al., 1962; Throop et al., 1989). Light passes through the watercored tissue more readily than the non-symptomatic tissue, which tends to scatter the light. As a result, a greater portion of the incoming light passes through the fruit. Trebor Industries developed a hand-held device for detecting watercore on individual fruit using transmitted light. More recently, several companies (e.g. Greefa iFA, Compac TasteTech, Fig. 6) offer internal defect detection, which includes the ability to detect watercore (in addition to internal browning) using visible and near infrared (NIR) wavelengths. In these technologies, light is shone into the fruit and the loss in the intensity of light eimissions fromthe fruit (or lack thereof in the case of watercore) is determined, permitting rapid and effective sorting.

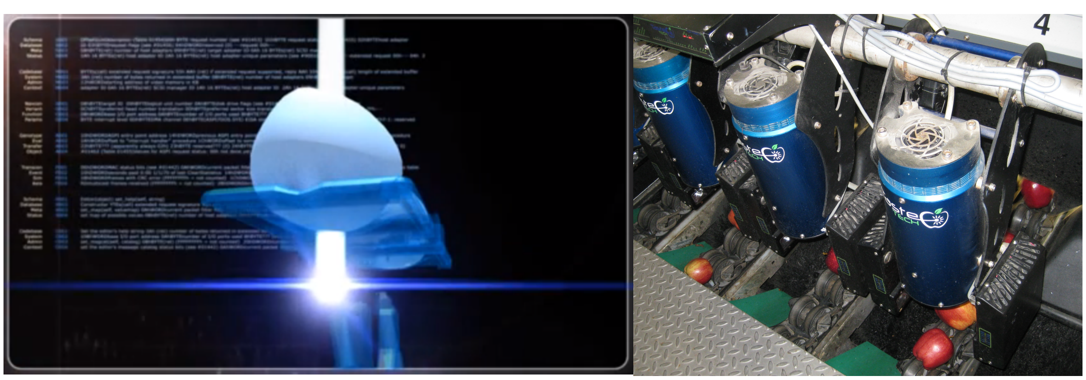

Figure 6. Images of Greefa (left) and Compac (right) technologies for internal defect detection and fruit sorting.

In addition to floatation and light transmission, a few more esoteric technologies have been investigated. Nuclear magnetic resonance (NMR) imaging (a.k.a. MRI) is a technique that can easily identify areas of free water in fruit or other tissues, wielding cross-sectional images (Fig. 7) in a few seconds to minutes time (Wang et al., 1988). While the technology is effective, it is too slow for practical applications requiring 10 or more fruits to be analyzed per second. Very high energy requirements are also a hindrance.

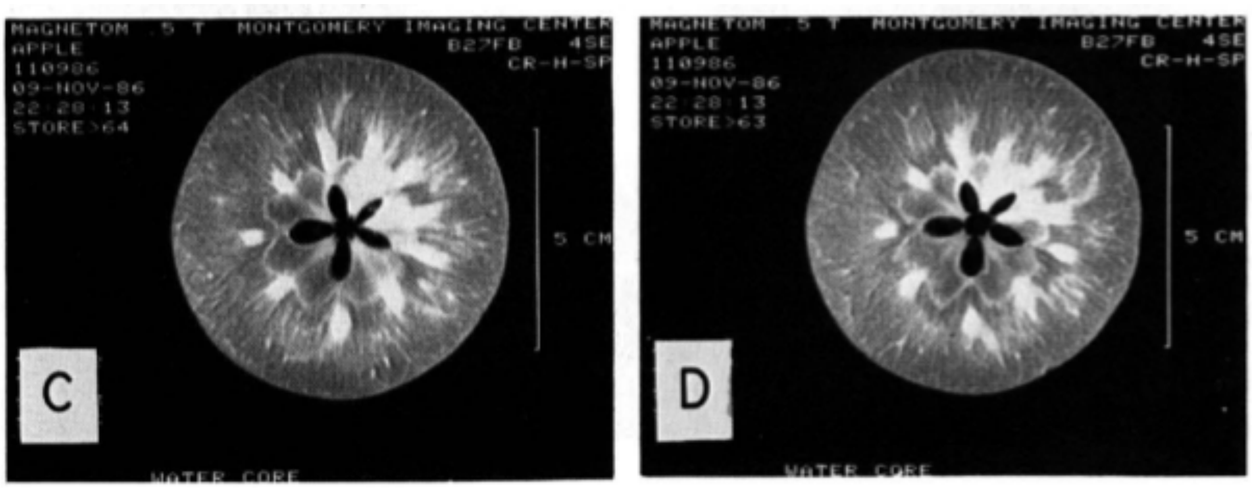

Figure 7. Nuclear magnetic resonance imaging of watercore in Red Delicious fruit (from Wang et al., 1988).

In a study comparing the effectiveness of X-ray computed tomography (X-ray CT) and MRI, the two technologies were similarly able to image and detect watercore in apple (Herremans et al., 2013, Fig. 8). Interestingly, the X-ray CT images could be used to image individual cells in the cortex and clearly show the accumulation of liquid between cells. The technique is slow, however, requiring several minutes to acquire a single image.

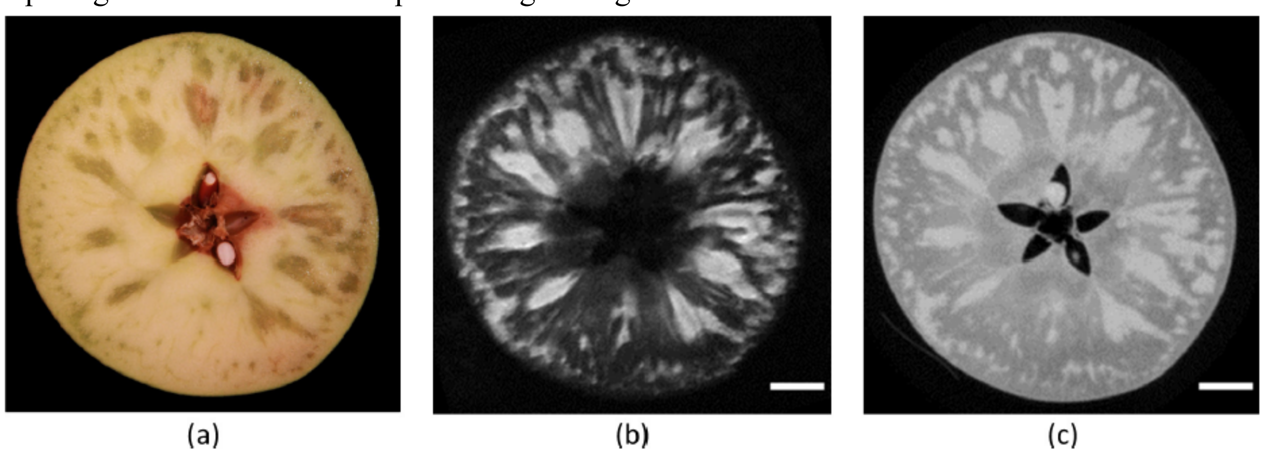

Figure 8. Watercore-containing 'Rebellon' apple fruit and its X-ray CT image (right) and MRI image (center).

Finally, thermal imaging can be used to detect watercore (Baranowski et al., 2008). This technique involves heating the fruit and measuring the rate of warming ising thermal images (Fig. 9).

Watercored fruit, likely because of the greater thermal mass and poorer air circulation, was slower to warm. While the technique is able to discriminate fruit correctly about 80% of the time, the time to acquire the data was over an hour and would be of little use in sorting. In addition, this technique requires precise temperature control, which is managed only with some difficulty.

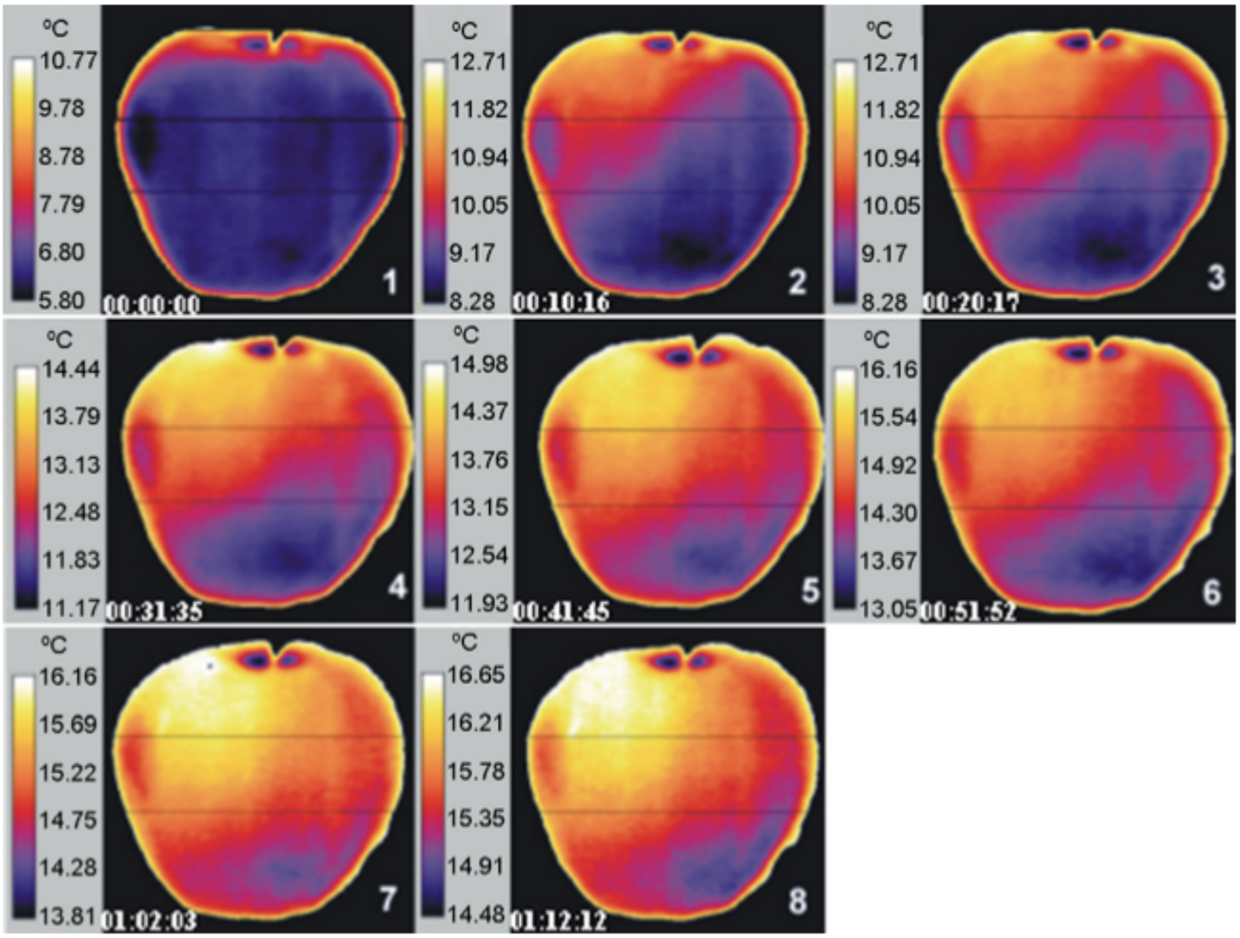

Figure 9. Thermography used for watercore detection (from Baranowski et al., 2008)

CONCLUDING COMMENTS

After more than a century of work, the root causes of watercore are still somewhat mysterious. While we know symptoms are linked to the fruit's inability to properly manage incoming photosynthate, the determining factor is still unknown. Importantly, though, we know that the disorder is linked to advancing maturity on the tree, so that further symptom development can be stopped simply by harvesting the fruit. While symptoms dissipate in air and CA storage, fruit with anything more than mild watercore symptoms should be marketed as soon as is practicable. Prior to storage and post-storage, detection and sorting can be rapidly performed with modern NIR sorting systems. The grower can minimize watercore development by establishing a balanced production system in which undercropping is prevented. In addition, a timely harvest before maturity becomes too advanced is critical in preventing this disorder from becoming too severe.

Table 1. List of cultivars with reported susceptibility (Yes) or resistance (No) to watercore (Marlow and Loescher, 1984).

Cultivar	Watercore susceptibility	Cultivar	Watercore susceptibility
Alfriston	Yes	Northwest Greening	Yes
Allington Pippin	Yes	Oldenburg	Yes
Antonovka	Yes	Ontario	Yes
Arkansas	Yes	Pioneer	Yes
Baldwin	Yes	Pound Sweet	Yes
Ballarat	Yes	Pumbkin Sweet	Yes
Beacon	Yes	Ramo	Yes
Ben Davis	Yes	Red Canada	No
Blenheim	Yes	Red Delicious	Yes
Braeburn	Yes	Red Miller	Yes
Bramley Seedling	Yes	Red St. Lawrence	Yes
Breton Henry	Yes	Reinette d'Angleterre	Yes
Calville Blanc	Yes	Rhode Island Greening	Yes
Cleopatra	Yes	Ribston Pippin	Yes
Commerce	Yes	Richared	Yes
Cortland	No	Rival	Yes
Cox's Orange Pippin	Yes	Rogers Red	Yes
Delicious	Yes	Rokewood	Yes
Democrat	Yes	Rome	Yes
Devonshire Quartredon	Yes	Rome Beauty	Yes/No
Dougherty	Yes	Roval Red	Yes
Duchess	Yes	Russian	Yes
Dunns	Yes	Scarlet Nonpareil	Yes
Early Harvest	Yes	Spitzenberg	Yes
Fall Pippin	Yes	Stark	Yes
Fameuse	No	Starking	Yes
French Crab	Yes	Starkrimson	Yes
Fuji	Yes	Statesman	Yes
Gano	No	Stayman	Yes
Gardner Red	Yes	Stayman Winesap	Yes
Glori Mundi	Yes	Stone Pippm	Yes
Golden Delicious	Yes/No	Sturdeespur	Yes
Granny Smith	Yes	Sturmer Pippin	Yes
Gravenstein	Yes	Suntan	Yes
Grimes Golden	Yes	Tasmans Pride	Yes
Holstein Cox	Yes	Tompkins King	Yes
Honeycrisp	Yes	Tolman	Yes
Irish Peach	Yes	Transparent	Yes
Jacobs Sweet	Yes	Turner Red	Yes
James Grieve	Yes	Twenty Ounce	Yes
Jardine Red	Yes	Verde Doncella	Yes
Jonathan	No/Yes	Virginia Summer Rose	Yes

King	Yes	Wagener	Yes
King David	Yes	Wealthy	Yes/No
Kinnard	Yes	White Astrachan	Yes
Lady	Yes	Willow Twig	Yes
Lalla	Yes	Winesap	Yes
Lane's Prince Albert	Yes	Winter Banana	Yes
London Pippin	Yes	Winter Golden Pearmain	Yes
Lord Derby	Yes	Wolf River	Yes
Lord Wolseley	Yes	Worcester	Yes
Margil	Yes	Worcester Pearmain	Yes
Mela Carlo	Yes	Yates	Yes
Miller's Seedling	Yes	Yellow Bellflower	Yes
Morgendotl	Yes	Yellow Newton	Yes
Mcintosh	No	Yellow Transparent	Yes
Newton	Yes	York Imperial	Yes
Northern Spy	Yes/No	Zurich Transparent	Yes

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