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Susceptibility to Chilling Injury of Peach, Nectarine, and Plum Cultivars Grown in California

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Abstract. **The susceptibility to chilling injury (CI) or internal breakdown (IB) was evaluated in the most currently planted yellow- and white-flesh peach [*Prunus persica* (L.) Batsch] and nectarine [*Prunus persica* var. nectarine (L.) Batsch] and plum [*Prunus salicina* Lindel] cultivars from different breeding sources and fruit types. Cultivars were segregated into three categories (Cat. A, B, and C) according to their susceptibility to CI or IB symptoms (mealiness and flesh browning) when exposed to 0 °C or 5 °C storage temperatures. Cultivars in Cat. A did not develop any symptoms of CI after 5 weeks of storage at either temperature. Cultivars in Cat. B developed symptoms only when stored at 5 °C within 5 weeks of storage. Cultivars were classified in Cat. C when fruit developed CI symptoms at both storage temperatures within 5 weeks of storage. Most of the yellow- and white-flesh peach cultivars developed IB symptoms when stored at both storage temperatures (Cat. C). Most of the new nectarine cultivar introductions did not develop CI symptoms when stored at 0 °C or 5 °C after 5 weeks (Cat. A). Three out of six plum cultivars tested had CI symptoms within 5 weeks storage at 0 °C. However, all of the plum cultivars tested developed CI symptoms when stored at 5 °C (Cat. B). The importance of proper temperature management during postharvest handling was demonstrated.**

Peach, nectarine, and plum fruit are highly perishable and may deteriorate quickly at room temperature. Low temperature during storage and/or shipping extends fruit market life. However, fruit from some cultivars develop lack of juiciness (mealiness or woolliness), flesh browning, black pit cavity, flesh translucency (gel breakdown), red pigment accumulation (bleeding), fail to ripen, and lose flavor after prolonged cold storage and/or after ripening at room temperature. In previous publications from South Africa, the lack of juiciness in ripe peaches and nectarines has been named woolliness (Von Mollendorff, 1987, 1992), while flesh translucency in plums has been called gel breakdown (Dodd, 1984). These symptoms are also reported as internal breakdown (IB) or chilling injury (CI) (Mitchell and Kader, 1989; Smith, 1934; Von Mollendorff et al., 1992). As the terms CI and IB include the symptoms listed above, we will refer to them only as CI to avoid potential confusion. Since these symptoms mainly develop during fruit ripening after cold storage, this problem is usually not noticed until fruit reaches consumers (Bruhn et al., 1991; Crisosto et al., 1995). The onset of these symptoms determines the postharvest storage/shipping potential because CI development reduces consumer acceptance (Crisosto et al., 1997). Susceptibility to CI varies according to genetic background (Anderson, 1979; Dodd, 1984; Harding and Haller, 1934; Hartman, 1985), maturity (Von Mollendorff, 1987), and orchard factors (Crisosto et al., 1995, 1997).

The objective of this work was to evaluate the influence of postharvest temperature (0 vs. 5 °C) conditions on the susceptibility of the most important California stone fruit cultivars to CI. Cultivar storage/shipping potential at both temperatures is fundamental in developing prepackaging, storage, shipping, and retail postharvest handling protocols for stone fruit. For a long-term solution, the variability in CI susceptibility among cultivars is valuable to geneticists and breeders to develop stone fruit cultivars free of CI, to understand the genetic inheritance of CI, and to locate the genes related to these disorders. In addition, this new information is important for plant physiologists to design fundamental studies to improve the basic understanding of the CI problem.

Materials and Methods

Twenty-five nectarine, 32 peach, and six plum cultivars, commercially grown in California, were tested for susceptibility to CI. All cultivars were picked at the California Well-mature stage according to the California Tree Fruit Agreement (CTFA) ground-color chips. For each cultivar, a 100-fruit sample was collected from each of three trees (replications) growing at the Kearney Agricultural Center (KAC) or from other commercial orchards with similar management conditions near the KAC. Outer canopy, medium-size fruit were sampled from the same canopy position height. Fruit were forced-air cooled to 0–2 °C within 6 h of harvest and then stored at either 0 or 5 °C (with 90% relative humidity) for up to 5 weeks. A postharvest fungicide dip (1.2 $g \cdot L^{-1}$ of iprodione) was used after the washing operation before packaging.

Weekly, three groups of 10-fruit samples from both storage temperatures (0 and 5 °C) were ripened (at 20 °C) until firmness reached between 10–18 N (measured with a UC–Davis penetrometer with a 7.9-mm tip) prior to CI symptom evaluation. The ripening period prior to CI evaluation varied from 3 to 7 d according to cultivar softening rate. We ensured that fruit were soft, but not mushy, for the CI evaluation. Fruit were evaluated for different manifestations of CI, such as lack of juiciness (mealiness or woolliness), flesh browning, flesh bleeding, and flesh translucency (gel breakdown). Observations were made on the mesocarp and the area around the pit immediately after the fruit were cut transversely to the plane of the suture. Fruit that had a dry appearance and little or no juice after hand squeezing were considered mealy or woolly. Fruit were also informally tasted for a feeling of graininess (like sand in the mouth) and/or "off flavors" to corroborate visual mealiness (woolliness) assessment. Fruit with uniform non-marked margin browning areas spreading from the pit cavity into ≥25% of the flesh area were considered commercially affected with flesh browning (Mitchell and Kader, 1989; Nanos and Mitchell, 1991). Storage/shipping potential was subjectively defined as the number of weeks each cultivar lasted without exceeding 20% mealiness or 15% flesh browning symptoms (≥25% of the flesh area).

According to their storage/shipping potentials at each storage temperature, the cultivars were classified into the following three categories: A. CI nonsusceptible and temperature insensitive (fruit with at least 5 weeks of storage/shipping potential at both temperatures); B. CI nonsusceptible (at least 5 weeks of storage/shipping potential) at 0 °C but CI susceptible (<5 weeks of storage/shipping potential) at 5 °C (temperature sensitive); C. CI susceptible (<5 weeks of storage/shipping potential) at both storage temperatures.

Results and Discussion

Mealiness and flesh browning were the major CI symptoms among most of the peach, nectarine, and plum cultivars tested (Tables 1–3). Flesh bleeding as a consequence of CI was observed in only a few cases. The type of symptoms and the storage/shipping potential based on CI depended on the cultivar and storage temperature. Most of the CI susceptible cultivars developed mealiness and flesh browning symptoms, but a few of the cultivars developed mealiness without flesh browning. Finally, a large group of cultivars did not develop any mealiness or flesh browning symptoms. For plums, development of flesh browning was always accompanied by flesh translucency (gel breakdown).

In all of the peach, nectarine, and plum

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Table 1. Effects of storage temperature on storage/shipping potential in peach cultivars.[z]

Cultivar[y]	Plant breeding program	Fruit type: Fruit	Fruit type: Flesh texture	Harvest date week/month	Storage/shipping potential (weeks) 0 ºC	Storage/shipping potential (weeks) 5 ºC
Yellow-fleshed cultivars						
Sweet Scarlet	Zaiger	Freestone	Nonmelting	1/June	4	2
June Lady	Merrill	Cling	Melting	1/June	4	1
Flavorcrest	Weinberger	Freestone	Melting	2/June	4	2
Summer Lady	NA	Freestone	Melting	3/July	5	3
Elegant Lady	Merrill	Freestone	Melting	4/June	4	1
Fay Elberta	NA	Freestone	Melting	3/July	4	3
O'Henry	Merrill	Freestone	Melting	4/July	3	2
Parade	Merrill	Freestone	Melting	3/August	1	<1
Fairtime	USDA	Freestone	Melting	3/August	3	1–2
Ryan Sun	Chamberlain	Freestone	Melting	1/August	4	1–2
Carnival	Merrill	Freestone	Melting	4/August	2	1
September Sun	Chamberlain	Freestone	Nonmelting	3/August	3	1–2
Last Chance	Sprague	Freestone	Melting	2/September	2	1
Autumn Lady	Merrill	Semifreestone	Melting	3/September	2	1
Autumn Rose	Richards	Freestone	Melting	2/October	1	1
White-fleshed cultivars[x]						
White Lady	Zaiger	Freestone	Melting	2/June	4	2
Sugar Lady	Zaiger	Freestone	Melting	3/June	4.5	3
Sugar Giant	Zaiger	Freestone	Melting	4/June	5	2.5
Summer Sweet	Zaiger	Freestone	Melting	2/July	4.5	2
September Snow	Zaiger	Freestone	Melting	4/August	4	2

[z]Information was obtained from personal communications with Gary Van Sickle, Kevin Day, and David Ramming, from Brooks and Olmos (1972), Whealy and Demuth, (1993), Okie (1998), and nursery catalogues.
[y]All cultivars exhibited mealiness and flesh browning except 'Sweet Scarlet' and 'Sugar Giant', in which mealiness was evident without flesh browning.
[x]All susceptible to internal breakdown at both temperatures.

Table 2. Effects of storage temperature on storage/shipping potential in nectarine cultivars.[z]

Cultivar[y]	Plant breeding program	Fruit type: Fruit	Fruit type: Flesh texture	Harvest date week/month	Storage/shipping potential (weeks) 0 ºC	Storage/shipping potential (weeks) 5 ºC
(Cat. B) Nonsusceptible to CI at 0 ºC, susceptible at 5 ºC						
Spring Red	Anderson	Freestone	Melting	2/June	5+	3
Summer Grand	Anderson	Freestone	Melting	1/July	5+	5
(Cat. C) Susceptible to CI under both temperatures						
Summer Bright	Bradford	Clingstone	Melting	1/July	5	3
Summer Fire	Bradford	Clingstone	Melting	3/July	5	3
Ruby Diamond	Bradford	Freestone	Melting	3/June	5	3
August Red	Bradford	Clingstone	Melting	2/August	5	3
September Red	Bradford	Clingstone	Melting	3/August	4	1

[z]Information was obtained from personal communications with Gary Van Sickle, Kevin Day, and David Ramming, from Brooks and Olmos (1972), Whealy and Demuth, (1993), Okie (1998), and nursery catalogues.
[y]All cultivars exhibited mealiness.

Table 3. Effects of storage temperature on storage/shipping potential in plum cultivars[z].

Cultivar[y]	Plant breeding program	Fruit type	Harvest date week/month	Storage/shipping potential (weeks) 0 ºC	Storage/shipping potential (weeks) 5 ºC
(Cat. B) Nonsusceptible to CI at 0 ºC, susceptible at 5 ºC					
Blackamber	Weinberger	Freestone			
Fortune	Weinberger	Semiclingstone	2/June	5+	3
Angeleno	Garabedian	Semifree to freestone	1/July	5+	5
(Cat. C) Susceptible to CI under both temperatures					
Showtime	Wuhl	Freestone	1/July	5	3
Firar	Weinberger	Freestone	3/July	5	3
Howard Sun	Chamberlain	Freestone	3/August	4	1

[z]Information was obtained from personal communications with Gary Van Sickle, Kevin Day and David Ramming, from Brooks and Olmos (1972), Whealy and Demuth, (1993), Okie (1998), and nursery catalogues.
[y]All cultivars exhibited flesh browning and flesh translucency (gel breakdown) except 'Angeleno', 'Friar', and 'Howard Sun' which also exhibited mealiness.

cultivars, storage/shipping potential was longer at 0 °C than at 5 °C. Storage/shipping potential determined at 5 °C varied from <1 week to >5 weeks. Storage/shipping potential at 0 °C varied from 3 to >5 weeks. Among the 22 yellow-flesh peach cultivars, five ('David Sun', 'June Sun', 'Kern Sun', 'Crown Princess', and 'Rich Lady') did not develop any mealiness and/or flesh browning symptoms after 5 weeks at either storage temperature (Cat. A). Two peach cultivars ('Crimson Lady' and 'Zee Lady') did not show symptoms when stored at 0 °C for at least 5 weeks, but they developed CI at 5 °C (Cat. B). 'Crimson Lady' and 'Zee Lady' had 3 and 2 weeks of storage/shipping potential when stored at 5 °C, respectively. The other 15 peach cultivars (Cat. C) developed CI symptoms at either temperature (Table 1). Among the yellow-flesh peaches, early harvest cultivars (May–June) were the least susceptible to CI and not affected by storage temperature. Middle-season cultivars (July–August) were less susceptible to CI at 0 °C but highly susceptible to CI at 5 °C. Late-harvest cultivars were susceptible to CI at both temperatures.

Of the white-flesh peach cultivars, 'Snow Flame', 'Champagne', and 'Snow Brite' were not CI susceptible at either storage temperature (Cat. A). 'Snow Giant' and 'Snow King' cultivars did not develop CI symptoms at 0 °C, but they did at 5 °C (Cat. B). When fruit were exposed to 5 °C, storage/shipping potential for 'Snow Giant' and 'Snow King' was reduced to 3 and 1.5 weeks, respectively. 'White Lady', 'Sugar Lady', 'Sugar Giant', 'Summer Sweet', and 'September Snow' were CI susceptible at both storage temperatures (Cat. C.). Among the white-flesh peach cultivars, the harvest season (early, middle, or late) did not affect CI susceptibility (Table 1). In the white-flesh peach cultivars, the storage/shipping potential at 0 °C and 5 °C varied from >3 to >5 weeks, and 1.5 to >5 weeks, respectively.

'Rose Diamond', 'May Glo', 'Zee Grand', 'Sparkling May', 'Early Diamond', 'Spring Bright', 'May Diamond', 'Sun Diamond', 'Red Diamond', 'Honey Kist', and 'Royal Glo' yellow-flesh nectarine cultivars did not develop CI symptoms at either temperature when stored for >5 weeks (Cat. A). 'Summer Bright', 'Summer Fire', 'Ruby Diamond', and 'August Red' cultivars had a storage/shipping potential at 0 °C of 5 weeks. 'Spring Red' and 'Summer Grand' classified at Cat. B, but they also had a storage/shipping potential at 0 °C of >5 weeks. When 'Spring Red', 'Summer Bright', 'Summer Fire', 'Ruby Diamond', and 'August Red' were stored at 5 °C, storage/shipping potential was reduced to 3 weeks. Storage/shipping potential was reduced to 5 weeks when 'Summer Grand' was stored at 5 °C. 'September Red' was the only yellow-flesh nectarine cultivar classified in Cat. C; the fruit started to show CI symptoms by the fourth and first weeks when stored at 0 and 5 °C, respectively (Table 2).

'Arctic Star', 'Arctic Glo', 'June Pearl', and 'Arctic Rose' white-flesh nectarines did not develop CI symptoms at either storage temperature for at least 5 weeks (Cat. A).

'Arctic Queen', 'Fire Pearl', and 'Bright Pearl' developed CI symptoms only when stored at 5 °C (Cat. B). In these three cultivars, storage/shipping potential was reduced from >5 weeks to 3 weeks when fruit were stored at 5 °C instead of 0 °C.

'Blackamber', 'Fortune', and 'Angeleno' plum cultivars did not develop CI symptoms when stored at 0 °C for 5 weeks (Table 3). 'Show Time', 'Friar', and 'Howard Sun' developed CI symptoms within 4 weeks even when stored at 0 °C. In all of the plum cultivars, longer storage/shipping potential was achieved when stored at 0 °C than at 5 °C (Table 3). No relationship between harvest season (early, middle, or late) and susceptibility to flesh browning and translucency was detected. Early harvest cultivars such as 'Showtime', 'Blackamber', and 'Fortune' developed lack of juiciness in addition to the flesh browning and translucency symptoms.

CI or IB are the terms used to describe the physiological disorder symptoms that develop during fruit ripening after low-temperature storage. These disorders include changes in the fruit flesh such as mealiness, browning, bleeding, and lack of flavor (Anderson, 1979; Crisosto et al., 1997; Dodd, 1984; Hartman, 1985; Smith, 1934). This work indicated that mealiness and flesh browning were the major CI symptoms for peach, nectarine, and plum cultivars grown under California conditions. Most peach cultivars were susceptible to both mealiness and flesh browning. Most of the plum cultivars expressed CI symptoms as flesh translucency associated with flesh browning. Most of the nectarine cultivars were not susceptible to mealiness or flesh browning. No nectarine or plum cultivars developed mealiness or browning symptoms when stored at 0 °C for up to 4 weeks.

Flesh bleeding as a consequence of CI was visible in a few cultivars, but it was less important than mealiness and flesh browning. In new nectarine cultivars, the formation of red color in the flesh (bleeding) was not related to CI symptoms or "off flavor." For example, in 'Summer Bright' and 'Summer Fire' nectarines, formation of red color in the flesh did not affect taste but it was related to fruit maturity rather than storage temperature (unpublished data).

In 71% of the CI susceptible peach and nectarine cultivars tested, mealiness and flesh browning symptoms were observed. Mealiness symptoms developed prior to flesh browning, but in a few cultivars mealiness and flesh browning developed at the same time. In the cultivars tested, flesh browning was not observed without mealiness symptoms; although 30% of CI susceptible peach and nectarine cultivars developed mealiness without flesh browning. Only in early harvest plum cultivars were flesh browning and translucency (gel breakdown) symptoms observed without mealiness.

Among the yellow-flesh peach and nectarine cultivars, 16 of the 18 freestone peach cultivars were susceptible to CI, while one of the four clingstone peach cultivars was CI susceptible. Of the 11 freestone nectarine cultivars, only three were susceptible to CI. Four of the seven clingstone nectarine cultivars were CI susceptible. Within the same group, 14 of the 15 melting flesh peach cultivars were susceptible to CI, while only three of the seven yellow and nonmelting flesh peach cultivars were CI susceptible. Among the 18 melting yellow flesh nectarine cultivars evaluated, seven were CI susceptible. No nonmelting flesh nectarine cultivars were evaluated. Since most of the white-flesh peach cultivars were freestone and melting, and most of the white-flesh nectarine cultivars were clingstone and melting, we did not relate CI susceptibility with these fruit types and flesh characteristics.

In all of CI susceptible cultivars, the development of mealiness and flesh browning symptoms was delayed, and also the intensity of flesh browning was lower when the fruit were stored at 0 °C rather than 5 °C. Smith (1934) reported that CI is induced when fruit are stored under 10 °C for a prolonged period. Others reported that CI develops more rapidly in fruit held at 3 to 5 °C than in fruit stored at 0 °C.

This work points out the detrimental effect of even 7-d exposure to 5 °C storage temperature on postharvest storage/shipping potential. In some peach cultivars ('Forty Niner' and 'Rio Oso Gem'), even 3-d exposure at 5 °C may significantly reduce storage/shipping potential (Crisosto, unpublished). Thus, proper postharvest temperature management (near 0 °C) during storage, shipping, and retail marketing can extend peach, nectarine, and plum postharvest storage/shipping potential. For those cultivars that develop mealiness and/or flesh browning symptoms within 1 or 2 weeks under both storage temperatures, rapid marketing is recommended. Other benefits of low temperature storage of peaches, nectarines and plums are the reduction of decay development, water loss, flesh softening, and respiration (Mitchell, 1987; Mitchell and Kader, 1989). Since stone fruit often encounter 5 °C temperatures during the postharvest handling process (Crisosto unpublished), this information provides guidance for growers, packers, shippers, handlers, and retailers in designing their postharvest strategy. Special supervision and enforcement of proper postharvest temperature management should be carried out on cultivars that are CI susceptible.

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