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Cooling Method Influences the Postharvest Quality of Broccoli

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***Abstract*. The effects of cooling method and packaging with perforated film on broccoli (*Brassica oleracea* L. Italica group) quality during 2C storage were studied. Broccoli was either room-cooled, top-iced, or hydrocooled before being placing into storage for 14 days. Hydrocooling was the most rapid cooling method and resulted in the lowest vapor pressure deficits between the broccoli and the surrounding air. Hydrocooling and top-icing resulted in similar firmness and color retention. Broccoli that was hydrocooled and then overwrapped with perforated film lost less weight, was firmest, and retained color better than either top-iced or room-cooled broccoli.**

Broccoli has high respiration and transpiration rates and a short shelf life (Brennan and Shewfelt, 1989). Rapid cooling after harvest is important in reducing metabolic activities that can result in deterioration (Brennan and Shewfelt, 1989). Broccoli can be stored for several weeks under ideal low-temperature and high-humidity conditions but can deteriorate rapidly at temperatures >1 to 2C and humidities <95% (Ryall and Lipton, 1979; Shewfelt et al., 1983). Low temperature and high humidity are difficult to maintain throughout the marketing chain, so there can be significant quality loss because of wilting and yellowing.

Field-packed broccoli often is liquid- or slush-iced in California (Mitchell, 1992), but in British Columbia and other parts of North America, broccoli is top-iced to help maintain low temperatures and reduce water loss (Ryall and Lipton, 1979). Bins or boxes of broccoli covered with crushed or flaked ice are placed in refrigerated storage and then transported. The result is that the weight of the ice increases transportation and handling costs and the spread of microbial populations in the melt-water (Brackett, 1989; Klieber and Wills, 1991). Adequate refrigeration during transport and marketing can eliminate the need for top-icing to control temperatures, but other strategies are required to reduce water loss and prevent wilting.

Postharvest wilting can be delayed by precooling as effectively as by top-icing (Klieber et al., 1993). Another alternative to top-icing is packaging broccoli in film that maintains high humidity around the produce (Wang and Hruschka, 1977). Much of the current research on packaging broccoli has focused on modified-atmosphere packaging (MAP), in which produce respiration modifies the atmosphere in the package by increasing CO_2 and decreasing O_2 concentrations (Ballantyne et al., 1988; Barth et al., 1993; Forney and Rij, 1991). Although MAP can be effective in reducing water loss, off-odors and off-flavors can result when CO_2 levels become too high or O_2 levels too low. This increase in CO_2 and O_2 levels is due to over-modification of the package atmosphere (Forney et al., 1991; Wang and Hruschka, 1977), especially when storage temperatures are undesirably high. Micro-perforated packaging reduces weight loss by maintaining high humidity around produce without over-modification of the atmosphere (Bracy et al., 1992; Geeson, 1989; Wang and Hruschka, 1977) and therefore avoids off-flavors.

Postharvest weight loss and wilting relate directly to vapor pressure deficit (VPD) rather than to relative humidity (RH) (Grierson and Wardowski, 1978). Any alternative to top-icing should reduce the VPD between the product and the surrounding air. Our study compares the postharvest cooling methods of room cooling, hydrocooling, and top-icing. We also investigated overwrapping broccoli in micro-perforated packaging to examine the packaging's effect on VPD, weight loss, color retention, and firmness during 2C cold storage.

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Materials and Methods

Broccoli were grown at the Agriculture Canada Research Station, Agassiz, Canada, and were harvested Aug. 1993. Each head was trimmed to 15 cm total length, and the trimmed heads weighed between 200 and 350 g.

We performed two experiments: the first experiment evaluated the postharvest treatment effects on the product temperature characteristics and the second evaluated the effects on quality changes in the product during storage.

Temperature changes. Thermocouples were placed in the core and floret tissue of freshly harvested broccoli heads. Temperature data were recorded and averaged every minute with a 21× micrologger (Campbell Scientific, Edmonton, Alberta, Canada). Six broccoli heads with thermocouples were placed in each of three replicate plastic bins per treatment. Broccoli heads were given one of three postharvest cooling treatments: 1) passively room-cooled at 2C with 95% ± 2% RH, as described by Perrin (1988); 2) top-iced with 4 kg of flaked ice then placed in 2C storage; or 3) hydrocooled for 12 min using water at 1C. In two other treatments, hydrocooled and nonhydrocooled broccoli heads were overwrapped with micro-perforated wrap (SM60 Cryovac; W.R. Grace & Co., Duncan, S.C.), and thermocouples were used to measure the internal atmosphere temperature of each package. Then, all broccoli in the five treatments were placed in 2C storage for 95 h.

Quality changes. Changes in weight, firmness, and color of the broccoli heads were monitored during 2 weeks of storage at 2C. Ten freshly harvested broccoli heads were placed in each of three replicate bins for each of the five postharvest treatments. Room-cooled broccoli was either film-packaged or left naked and placed directly into 2C storage. Hydrocooled broccoli heads were either packaged or left naked and then placed into storage. Three bins were top-iced only with 4 kg flaked ice and then placed into storage.

Weight losses were estimated during 2C storage (on days 0, 3, 5, 7, 10 12, and 14) by weighing 15 individual heads for each treatment (±0.01 g). Two judges independently assessed the firmness (on a scale from 5 to 0 with 0.5 graduations, where 5 = very firm and 0 = totally flaccid) of 15 heads daily during 2 weeks of storage. A visual index (5 = dark green; 4 = medium green; 3 = green; 2 = slight yellowing; or light margins showing around floret clusters; 1 = mostly yellow) was used to measure color change of 15 heads during storage. The average value from two independent judges was recorded.

The broccoli head VPD was estimated for the first 90 min of storage by recording temperatures at the broccoli core and in the storage room. The air temperature inside a package was recorded by the microloggers as previously described. The broccoli vapor pressure (VP_{broc}) was determined by assuming that the broccoli tissue was at 100% RH. The VP_{broc}, therefore, was taken as the saturated vapor pressure (P_S) at the core temperature, with values obtained from psychrometic tables (American Society of Heating, Refrigerating, and Air-conditioning Engineers, 1981). The storage room was at 95% RH; therefore, the vapor pressure (VP_{room}) was calculated as: $VP_{room} = P_S \times 0.95$ for any given storage room temperature. The vapor pressure of the air within the packages (VP_{pack}) was calculated as $VP_{pack} = P_S \times 0.99$, assuming the air within the package was at 99% RH. The presence of condensation within the packages supports this estimate of the package air RH.

The VPD for naked broccoli then was calculated as $VPD = VP_{broc} - VP_{room}$ and for packaged broccoli as $VPD = VP_{broc} - VP_{pack}$.

Using SAS (1985), analysis of variance was used on broccoli core and floret temperatures. The SAS general linear models procedure was used to perform repeated measures analysis of variance on weight loss, firmness, and color data.

Results

The storage room temperature averaged 2.7C with defrost cycles occurring every 6 h. During the 1-h defrost cycle, temperatures increased to a maximum of 6.4C.

Temperature changes. For all treatments, florets had lower mean tissue temperatures than cores during the first 5 h of storage (Table 1). The mean temperatures of naked, hydrocooled, and top-iced florets were similar to the storage room air temperature. The mean temperature of room-cooled, wrapped florets was higher than the naked, hydrocooled, and top-iced florets. The mean core temperature of hydrocooled broccoli, whether naked or packaged, was lower than that of all other treatments. Room-cooled packaged and top-iced broccoli had the highest core temperatures during the first 5 h of storage (Table 1).

Hydrocooling resulted in the fastest cooling rate, reducing the tissue temperature of the broccoli from 22 to 6C in 12 min (Fig. 1). After placing broccoli into the 2C storage room, it took only 35 min for the core temperature of hydrocooled naked broccoli to reach the storage room temperature (Fig. 1); the core temperature of hydrocooled packaged broccoli took ≈45 min to cool similarly.

Table 1. Effect of cooling treatments on mean broccoli core and floret temperatures during the first 5 h in 2C storage.

Treatment	Packaged	Mean temp (°C) Core	Floret
Room-cooled	–	5.8	4.7
	+	9.5	7.3
Hydrocooled	–	3.3	3.2
	+	3.6	3.2
Top-iced	---	9.1	4.7
SE		0.6	0.5
Significance		**	**

**Significant at $P \leq 0.01$.

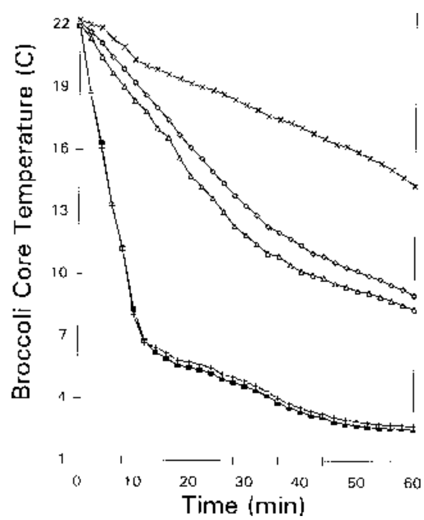

Fig. 1. Effect of cooling method on broccoli core temperatures (n = 32); (×) room-cooled packaged broccoli, (❑) top-iced broccoli, (Δ) room-cooled naked storage, (■) hydrocooled naked broccoli, and (+) hydrocooled broccoli packaged in micro-perforated wrap. The storage room was set at 2C and 95% ± 2% relative humidity.

Room-cooled packaged broccoli was the slowest to cool, taking ≈5.4 h to cool from 22 to 2C and took almost twice as long to cool (2.8 h) as room-cooled naked broccoli.

After the core reached the storage room temperature, the temperature of the packaged broccoli was more stable than that of naked broccoli during defrost cycles. During defrost cycles, the core temperature of the naked broccoli was ≈1C warmer than that of the packaged broccoli, and naked florets were ≈1.5C warmer than wrapped florets (Fig. 2).

The core temperature of broccoli that was top-iced and then placed in 2C storage took ≈4.8 h to reach the storage room temperature. The top-ice had melted by day 4. There was no difference between top-iced and room-cooled packaged broccoli core temperatures; both were slower to cool than room-cooled naked broccoli (Table 1).

Quality changes. Generally, there was a decrease in quality during the 14 days of storage (Table 2). Packaging was the most significant factor in reducing broccoli weight loss and maintaining firmness and color (Table 2). After 2 weeks of storage, packaged broccoli (whether hydrocooled or not) had 2.1% and 2.3% weight loss, respectively, compared to 11.1% for top-iced, 15.1% for room-cooled naked, and 15.0% for hydrocooled naked broccoli. Packaged broccoli also retained its firmness and color better than either top-iced or naked broccoli, whether hydrocooled or not (Table 2). Hydrocooled naked and top-iced broccoli were significantly firmer and greener than the room-cooled naked broccoli (Table 2).

Cooling method and packaging affected broccoli VPD (Fig. 3). Top-iced and room-cooled naked broccoli had similar VPDs. Warm broccoli placed directly in cold storage had the highest VPD and greatest weight loss. An increase in the VPD over time (peaking at 30 min) was observed in room-cooled packaged broccoli (Fig. 3). This increase in VPD occurs because the air surrounding the broccoli within the packaging is initially warmer than the storage room, resulting in an initially low VPD. The greatest temperature difference between room-cooled packaged broccoli and the surrounding air occurred after 30 min, when the air in the package equilibrates with the storage room. The highest VPD coincides with the greatest temperature difference between the broccoli and the surrounding air.

The advantage of rapidly cooling broccoli by hydrocooling is the resultant low VPD between the product and the surrounding air and consequent reduction of water loss during early stages of cold storage. There was a slight increase in VPD for hydrocooled broccoli during the first 30 min of storage because the temperature in the storage room was initially lower than that of the broccoli.

After 60 min in storage, there is still a difference between the VPDs of the different treatments, with hydrocooled packaged broccoli having the lowest VPD (Fig. 4).

Discussion

Broccoli quality declined during the 2 weeks in 2C storage for all treatments. By the end of the experiment, we considered only the packaged broccoli to be marketable. Loss of firmness was the major quality attribute rendering the product unmarketable. All

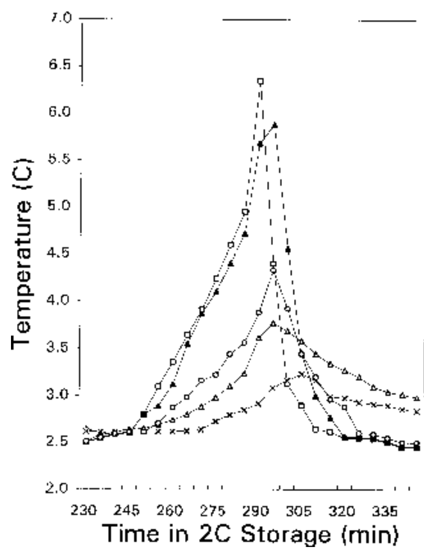

Fig. 2. The effect of defrost cycles in a 2C storage room on the (❒) air temperature and the average (n = 16) temperature of (×) packaged or (Δ) naked broccoli cores and (▲) naked or (❍) packaged broccoli florets.

Table 2. Effect of postharvest treatments on broccoli weight loss, firmness, and color during 14 days of storage at 2C.

Treatment	Wt loss (g/100 g)	Firmness[z]	Color rating[y]
Storage (days)			
0	0.0	5.0	5.0
3	1.3	4.8	5.0
5	2.5	4.2	4.8
7	4.0	3.7	4.7
10	6.6	3.2	4.3
12	8.2	2.9	4.0
14	9.2	2.8	3.7
SE	1.0	0.3	0.2
Significance[x]	L**, Q**	L**, Q**	L**, Q**
Cooling methods			
Room-cooled			
Naked	7.7	2.8	3.9
Packaged	1.1	4.7	4.9
Hydrocooled			
Naked	7.6	3.3	4.4
Packaged	1.0	4.9	4.9
Top-iced	5.9	3.3	4.4
SE	0.7	0.2	0.1
Significance	**	**	**

[z]Firmness was rated from 5 = very firm to 1 = totally flaccid.

[y]Color was rated from 5 = dark green to 1 = mostly yellow.

[x]L = linear; Q = quadratic.

**Significant at $P \leq 0.01$.

unpackaged broccoli, whether room-cooled, hydrocooled, or top-iced, was unacceptable by day 14 because of weight loss and the accompanying flaccidity.

Room-cooled naked broccoli had the highest weight loss and became limp and unmarketable rapidly. Similar to results of Klieber et al. (1993), hydrocooled and top-iced broccoli retained their firmness and color longer during storage than room-cooled naked broccoli. Top-icing is used to prevent water loss during marketing, and in this study, weight loss was lower for top-iced broccoli than for room-cooled and hydrocooled naked broccoli.

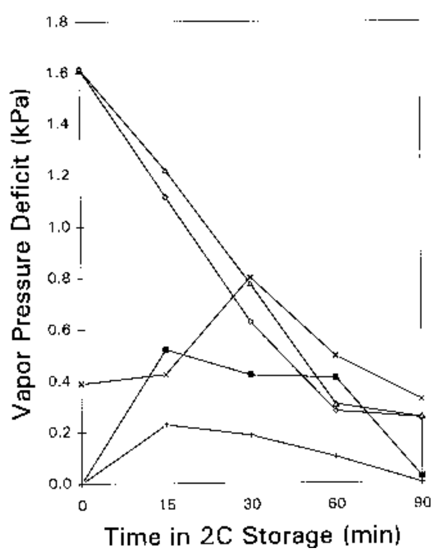

Fig. 3. The effect of cooling method and packaging on the vapor pressure deficit (VPD) of (×) room-cooled packaged broccoli, (◊) top-iced broccoli, (Δ) room-cooled naked storage, (■) hydrocooled naked broccoli, and (+) hydrocooled broccoli packaged in micro-perforated wrap. The storage room was set for 2C and 95% ± 2% relative humdity.

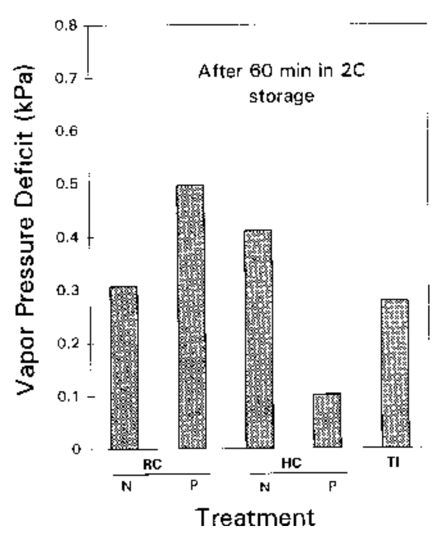

Fig. 4. Vapor pressure deficit (in kilopascals) of broccoli at 60 min in 2C storage. Abbreviations; RC = room-cooled, HC = hydrocooled, TI = top-iced, N = naked, and P = packaged.

Top-iced broccoli retained its firmness and color much better than room-cooled naked broccoli, and this result cannot be explained by differences in cooling rate. Top-iced broccoli did not cool faster than naked broccoli, and the two broccoli had similar VPDs. It seems likely that the melting ice rehydrates the broccoli, as indicated by lower weight loss in that treatment. Top-iced broccoli might have retained its firmness longer if the ice had been replaced regularly; however, replacing the ice would increase the product's handling costs.

From day 3 through day 14, hydrocooled naked broccoli was firmer than room-cooled naked broccoli. These results are similar to those reported by Forney and Rij (1991), who found that precooled broccoli retains its firmness better than broccoli that is not precooled. Hydrocooling rapidly lowers the tissue temperature of the broccoli, resulting in low VPDs when placing the broccoli in 2C storage that should result in lower weight loss. However, similar weight loss was observed between room-cooled and hydrocooled broccoli. In this experiment, broccoli was not weighed originally until after hydrocooling. Hydrocooling can add as much as 5% weight to broccoli (unpublished data). Thus, although hydrocooled and room-cooled broccoli lost similar weight, there were not identical losses in firmness because of this 5% weight advantage.

Micro-perforated packaging decreases weight loss by providing a high-humidity atmosphere around the broccoli (Bracy et al., 1992). Such packaging also helps retain the firmness of warm broccoli placed directly in storage because of the lower VPD between the internal package air and broccoli (compared to the VPD of the broccoli in relation to the storage air). Packaging insulates broccoli against cooling; room-cooled packaged broccoli cooled slowly. In this study, the air temperature inside the package remained above the ambient cooler temperature for >3 h. Packaging also acted as a buffer against the temperature fluctuations during the defrost cycles in the storage room. It also would be expected to buffer against transient periods of warmer temperature exposure during handling. The slowness of cooling top-iced broccoli may also have been due to an insulating quality of ice, when air pockets form as the ice melts due to respiratory heat produced by the broccoli.

Packaging was the most effective treatment for reducing weight loss and maintaining broccoli quality. Naked broccoli became rapidly unmarketable because of wilting. Hydrocooling is essential for the best postharvest quality of broccoli and was as effective as top-icing in retaining firmness and color in storage. Hydrocooling before packaging also improved the quality over room-cooled packaged broccoli.

As alternatives to top-icing, hydrocooling and packaging must continue to be explored to improve product quality and to reduce the energy costs incurred due to ice production and increased transportation costs due to the weight of ice used. At ideal storage temperatures, hydrocooling and packaging seem to be effective alternatives. Research on these alternatives at less than ideal temperatures needs to be pursued.

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