An Assessment of the Decay Hazard Associated with Hydrocooling Strawberries

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ABSTRACT

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The decay hazard associated with hydrocooling strawberries was related to whether they became inoculated with postharvest pathogens during the procedure. Storage of hydrocooled berries at warmer temperatures or for longer periods than recommended allowed inoculation to be expressed into disease. Cooling strawberries by immersion hydrocooling did not consistently lead to increased postharvest decays when compared with conventional forced-air cooling in two separate trials. No differences in decay incidence were found in berries that were hydrocooled versus forced-air cooled and then stored 7 days at 1°C plus 1 day at 20°C. With a 15-day storage regime (14 days at ≤7°C plus 1 day at 20°C), hydrocooled fruit developed less decay than forced-air–cooled fruit in one trial but more decay in a second. Wrapping baskets of cooled berries with plastic film promoted disease development and slowed the moisture loss from both hydrocooled and forced-air–cooled berries. The wrap did not promote disease more when applied to wet, hydrocooled berries as compared with dry, forced-air–cooled berries. Residual moisture left on the berries by the hydrocool treatment did not predispose the fruit to postharvest decays. In contrast, wounds and abrasions on hydrocooled fruit were temporarily water soaked and berries typically increased in weight as they were hydrocooled. Berries cooled in water containing spores of *Botrytis cinerea* or *Rhizopus stolonifer* developed nearly 100% decay incidence during a storage regime that favored specific development of gray mold (11 days at 7°C) or Rhizopus rot (2 days at 24°C). Chlorinating the hydrocooler water (120 mg of free chlorine per liter at pH 6.5) before adding the berries and spores reduced the incidence of gray mold to 43%; in contrast, berries hydrocooled in clean water developed 61% gray mold. Chlorination of the clean water led to significant reductions in the incidence of gray mold (44%) but did not affect the incidence of Rhizopus rot. The hydrocool method for cooling strawberries with the addition of proper chlorination has promise as a rapid method for cooling and cleaning berries and reducing gray mold inoculum on berry surfaces.

Strawberries (*Fragaria* × *ananassa* Duchesne) should be cooled rapidly after harvest to preserve quality and retard development of fruit rots. In tests in California on the relationship of berry quality in storage and interval between harvest and cooling berries to recommended storage temperatures, cooling berries from 29 to 4°C within 1 h of harvest led to the best quality and lowest incidence of postharvest decay in berries stored for a "normal" regime of 1 week at 4°C (21). By contrast, increased postharvest decays were associated with delays in cooling of 2 h or longer. A 6-h delay in cooling Florida-grown strawberries from 30 to <5°C led to increased softening and losses of moisture, vitamin C, and soluble solids during cold storage (22).

Under commercial conditions, the time from harvest to cooling strawberries varies widely, but delays longer than 2 h are not uncommon (8). Currently, forced-air cooling is recommended for cooling strawberries (19,20). Cold, humidified air drawn through stacks of packaged berries typically reduces pulp temperatures from 30 to <5°C within 1 h (8), although cooling times can be much longer, depending on carton configuration, how cartons are stacked, and cooler management (32). However, forced-air cooling can cause moisture loss from strawberries (19), which reduces their postharvest life (20).

Hydrocooling, in which products are immersed, sprayed, or drenched in cold water, maintains or slightly increases the moisture content of cooled products (19). Hydrocooling removes field heat from produce up to 15 times more rapidly than the forced-air method (5) and cleans products by removing chemical residues and debris (22). Hydrocooling has not been recommended for strawberries due to concerns that wetting harvested berries may lead to excessive postharvest decay (5,15, 20,27). Rose and Gorman (26), however, concluded that wetting strawberries did not, by itself, presage increased postharvest decays.

Excessive postharvest decays of many fresh fruits and vegetables have been associated with washing or cooling products, or with residual water left on products that have been washed or cooled (2). Inoculation of strawberry fruit by immersion in aqueous spore suspensions of pathogens is not well-documented although the addition of spores to wounds on strawberries has been widely used to initiate fruit rots. In most tests on postharvest decay in strawberries, the berries apparently were inoculated in the field during or prior to harvest. In a few reports, berries that were immersed in water or an aqueous spore suspension developed more decay than the respective controls. For example, Smith and Worthington (29) reported an average of 92% decay (primarily gray mold and Rhizopus rot) among berries that had been dipped into water ("wet check") versus 70% among "dry check" fruit. Horn (11) noted that 84% of fruit immersed in a suspension of *Botrytis cinerea* conidia decayed after treatment compared with 60% of those not immersed. The authors of these reports did not comment on the duration of berry wetness, which may have promoted development of natural infections. Free water from rainfall, dew, or irrigation promotes development of the two most serious diseases of strawberry fruit in the field, gray mold rot (*Botrytis cinerea* Pers.:Fr.) and Rhizopus rot (*Rhizopus* spp.) (18). Jarvis (14) found that spores of *B. cinerea* began to germinate in water films on berries within 1.5 h at 13°C and lesions appeared within 4 days if berries were wet for 8 h and within 2 days if wet for 10 h.

A clear association between cooling strawberries with water and increased decay has not been established, although circumstantial evidence suggests such berries would be decay prone. However, in several different trials hydrocooled strawberries retained better quality during storage than those cooled by other methods, whereas increases in decay incidence were not observed (7–9,25,26). For example, in one test berries were hydrocooled by immersion for 15 min or room-cooled for 6 h and then stored at 1 or 7.5°C for 7 days followed by 1 day at 20°C (8). Disease incidence was affected significantly by the storage temperature but not by the cooling method.

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The water in a hydrocooler designed for strawberries may require continuous sanitation to prevent berries from becoming inoculated by decay pathogens as they are cooled. Efficient hydrocoolers feature a continuous circulation of water from contact with product to cooling coils or ice blocks and back to the product (28). As berries move through the hydrocooler, pathogens on berry surfaces are likely to be washed into the water. How extensive pathogen accumulations would become during the cooling of strawberries isn't clear because the probable number of propagules of *B. cinerea*, *Rhizopus* spp., or other pathogens on disease-free strawberries has not been reported (18,31). Populations of *B. cinerea* on berry surfaces at harvest, however, were not considered as important to subsequent postharvest decays as were preharvest infections (18,24,31).

Water chlorination is currently the best, approved way to continuously sanitize water in hydrocoolers. However, water chlorination may not prevent strawberries from becoming inoculated as they are hydrocooled. Although chlorine quickly destroys microbes suspended in water, it is widely known to be ineffective on pathogen structures that are embedded in host tissues, appressed to product surfaces, enclosed in organic matrices such as clumps of decayed tissues, or suspended in water heavily contaminated with materials that react with chlorine (2,6). Moreover, chlorine is much less effective on suspended pathogen structures in water at 1°C compared with water at ≥20°C (6). With hydrocooled peach fruit, addition of chlorine products to the water provided inconsistent control of fruit rots (23,32). Boyette et al. (5) recommended the use of 55 to 70 mg of chlorine per liter in peach hydrocoolers, but advised that the chlorine would not kill all fungal spores on peach surfaces nor eliminate latent infections. Lill and Laundon (16) reported a slight decrease in decays in asparagus cooled to 4.4°C with chlorine concentrations of ≥67 mg/liter in the water compared with no chlorine. However, decay was not completely prevented even with free chlorine concentrations as high as 400 mg/liter.

The objectives of the present study were to determine if hydrocooling strawberries predisposes them to postharvest decays and if chlorination of the hydrocooler water would reduce or eliminate any predisposition found.

MATERIALS AND METHODS

Fruit. Strawberry fruit (cvs. Chandler, Oso Grande, and Sweet Charlie) were obtained from a commercial farm near Floral City, FL, during the 1992–93 and 1993–94 seasons. During the harvest, berries were placed in 10.5 × 10.5 cm polystyrene mesh baskets either by commercial crews or technical assistants, immediately transported to the Postharvest Laboratory, and sorted for color, size, and absence of defects.

Inoculum preparation. *Rhizopus stolonifer* (Ehrenb.:Fr.) Vuill. and *B. cinerea* were isolated from diseased strawberries and cultured on potato dextrose agar (PDA) in petri plates at 24°C. *B. cinerea* was grown on PDA in petri plates under continuous fluorescent light at 20°C and produced a uniform lawn of sporulation within 1 week. Cultures of the two pathogens that had been grown for 1 to 2 weeks were flooded with sterile, distilled water. One drop of Tween 80 was added to each dish of *B. cinerea.* Culture surfaces were brushed with a bent-glass spreader and the resulting suspension was poured into an Erlenmeyer flask. These stock suspensions were stored at 5°C for approximately 18 h. The spore concentration of *R. stolonifer* was determined with a hemacytometer, and the concentration of *B. cinerea* was calculated from a regression of optical density at 490 nm versus spore number that had been determined previously. Desired spore concentrations were made by dilution of the stock suspensions.

Effect of cooling method on decay incidence. Sweet Charlie strawberries harvested on 22 March, 2 April, and 12 April 1993 were temperature conditioned at 30°C and 75 to 80% relative humidity (RH) for 6 h. Ten berries that were completely red and uniform in size were placed in each basket and then cooled. Berries from the initial harvest were hydrocooled with or without chlorinated water. Berries from the second and third harvests were cooled by three methods: forced-air, hydrocooling with chlorinated water, or hydrocooling without chlorinated water. Berries cooled by forced-air were exposed to air at 1°C and 90 to 95% RH moving at the rate of 0.156 m^3/min/kg fruit with a pressure drop through the baskets of 75 Pa (22). Berry pulp temperatures fell from 30 to 5°C within 1 h except for those in trial 3, in which the air temperature was 5°C and the berries were cooled to 10°C. For the hydrocooled berries, baskets were inserted in nylon mesh citrus bags and fully immersed in 15 liters of cold tap water in an insulated plastic container with interior dimensions of 27.5 × 28.8 × 50 cm. The water was circulated with a submersible pump (Little Giant Pump Co., Oklahoma City, OK) and ice was added as necessary to maintain a water temperature of 1°C. Hydrocooled berries were cooled from 30 to approximately 2°C within 6 min based on thermocouple probe measurements of the pulp temperatures of a random sample of berries. In the water chlorination treatment, commercial liquid laundry bleach was added to the water to provide an initial free chlorine concentration of 200 mg/liter. The additions were based on the total chlorine concentration in the bleach, which had been determined by titration with sodium thiosulfate. The initial pH of the tap water was 8.4 and the pH of the chlorinated water was 9.0, which is somewhat higher than the range of pH levels (7.0 to 8.5) normally recommended for water chlorination (2).

Immediately after each cooling treatment, half of the baskets of berries were completely wrapped with 75-gauge PVC film (W44-75, RJR Filmco, Inc., Richmond, VA), which provided a vapor barrier that should delay drying of the water left on berries from the hydrocooling treatment as well as slow moisture loss from berries during storage. Cooled berries were stored in two regimes that simulated commercial handling and marketing of strawberries. The first regime was 7 days at 1°C and 90 to 95% RH followed by 1 day at 20°C, which would allow shipment to most domestic markets (20) and then retail sale through a nonrefrigerated display. The second regime involved a longer than ideal storage period at temperatures that ranged from 1 to 7°C and then a day at 20°C as described above. Such conditions might occur with surface shipment of strawberries to certain foreign markets; here, however, the 7°C temperature, which is a typical "compromise" temperature for storage rooms at produce wholesalers (15), was used to exacerbate development of gray mold while restricting the development of Rhizopus rot. In trial 1, temperatures in the storage room were inadvertently altered during the test, which led to a regime of 7 days at 1°C, 5 days at 15°C, 2 days at 7°C, and 1 day at 20°C. In trial 2, the regime was 7 days at 1°C, 7 days at 7°C, and 1 day at 20°C. In trial 3, the initial quality of the berries was low and featured a large number of bruises there were not detected until after the hydrocooling treatment. Therefore, the cold storage regime was held at 1°C for the entire 14-day period and was followed by 1 day at 20°C. After each storage regime, decay incidence was recorded. There were four baskets in each combination of cooling, chlorine, film wrap, and storage regime treatment.

Chlorine concentration required to kill spores of *R. stolonifer* and *B. cinerea* in cold water. Chlorine stock solutions were prepared as described above. The pH of chlorine stock solutions was reduced to 7.0 by addition of 1 M HCl. Test tubes (13 × 100 mm) were filled with 0.5 ml of a chlorine stock solution and then placed into the water reservoir of a PolyScience 960 refrigerated liquid circulator (Preston Industries, Inc., Niles, IL) set at 2°C for *B. cinerea* or 5°C for *R. stolonifer*. Three replicate tubes were used at each chlorine concentration. Stock suspensions of spores were cooled to the desired temperature and a 0.5-ml sample of each suspension was added to the chlorine solutions. Tubes were briefly vortexed and placed back in the water bath. After 2-min exposure, 0.1 ml of 0.1 M sodium thiosulfate was added to each test tube to inactivate residual chlorine. Next, 0.1-ml samples were removed

from each tube and spread onto duplicate petri plates (100 × 15 mm) containing PDA. The PDA plates were incubated on the bench top for 24 h (*R. stolonifer*) or 48 h (*B. cinerea*). The surface area covered by growth from surviving spores was estimated with the Horsfall-Barratt scale (12). In the first test with *R. stolonifer,* final free chlorine concentrations were 0, 10, 20, 40, and 80 mg/liter with 5×10^5 spores/ml. In the second test, the same chlorine concentrations were used in a factorial design with or without 5 g of Tween 80 per liter and 2.7×10^5 spores/ml. With *B. cinerea,* chlorine concentrations of 0, 20, 40, 80, and 120 mg/liter were used with or without 1 g of Tween 80 per liter and 2×10^6 spores/ml. In the second test with this organism, chlorine concentrations were 0, 40, and 120 mg/liter with or without 1 g of Tween 80 per liter and 8×10^5 spores/ml.

Effect of chlorination of hydrocooler baths on gray mold and Rhizopus rot in bruised strawberries. Aqueous spore suspensions of *B. cinerea* or *R. stolonifer* were prepared as described above and stored for 24 h at 5°C. Commercially harvested strawberries were obtained in the winter/spring of 1994 and handled as described above. For experiments with *R. stolonifer,* Oso Grande berries were obtained on 26 February and 14 March, Sweet Charlie on 28 February, and Chandler on 14 March. For experiments with *B. cinerea,* Chandler and Sweet Charlie berries were obtained on 18 March, and Oso Grande berries were obtained on 27 March. Prior to the hydrocool treatment, berries at 24°C were uniformly bruised to provide wounds likely to become water soaked during the cooling process. A bruise on one side of each berry was created by application of a static load of 9.8 Newtons for 2 s on a convex tip with a diameter of 15 mm (8). This bruise was similar to compression injuries that can accompany the removal of fruit from the plant by careless pickers (8,19). The berries were then hydrocooled from 24 to 3°C as described above. The treatments were arranged in a factorial design with 0 or 120 mg of free chlorine per liter and 0 or 1×10^4 spores/ml. The pH of the chlorine solution was reduced to 6.5 by the addition of 5 M HCl. There were four baskets each containing 10 fruit in each combination of treatments. After the cooling treatment, baskets of berries were removed, drained, and enclosed in polyethylene bags. Tops of the bags were folded loosely over to provide a moisture barrier that would not cause the composition of the atmosphere within the bags to change during the storage. In tests with *R. stolonifer,* berries were stored at 24°C for 2 days to allow rapid development of Rhizopus rot. When *B. cinerea* was used, berries were stored for 11 days at 7°C to prevent development of Rhizopus rot, which in a preliminary test prevented detection of the incidence of gray mold (30). After the incubation period, decay incidence was recorded for each basket of fruit.

Statistical analyses. In comparisons of cooling methods, data collected after each storage regime were analyzed in a randomized complete block design with dates and/or cultivars as blocks. The blocks were analyzed separately since a clear interaction occurred between block and cooling method. Means of the forced-air cooling treatments were compared with the means of the two hydrocooling treatments by orthogonal contrasts. In tests on effect of water chlorination on decay incidence, data sets were separated by pathogen and analyzed as a randomized complete block design with harvest dates/cultivars as blocks. Means of the chlorine treatments were compared by orthogonal contrasts with those of the nonchlorine treatments in both inoculum added and without inoculum treatments. All analyses were completed with the Statistical Analysis System software (SAS Institute, Inc., Cary, NC).

RESULTS

Effect of cooling method on decay incidence. Berries stored for 7 days at 1°C plus 1 day at 20°C had a decay incidence equal to or less than the 5% allowed by grade standards in 15 of 16 treatment combinations (Table 1). Decay incidence was not affected by cooling method or film wrap. Water chlorination did not reduce decay incidence among the hydrocooled berries. Gray mold was the most prevalent disease. Most of the lesions developed during the 20°C storage, whereas little disease was observed during a cursory examination of the berries as they were transferred from 1 to 20°C.

Storage of berries for 15 days, with or without the ideal storage temperature of 1°C, led to a decay incidence that was usually much higher than the allowable 5% (Table 1). Most of the lesions became visible during the last day of the storage regime when pulp temperatures warmed to 20°C, although certain berries were covered with gray mold at the time of transfer. The average disease incidence among the berry lots used in the tests varied from 10 to 42%. The highest incidence observed was found in trial 3 among berries that had been harvested after the commercial season was over.

Decay incidence after the 15-day storage regime was inconsistently affected by the cooling methods, whereas chlorination of the water had no apparent effect (Table 1). In one comparison of hydrocooling with forced-air cooling (trial 2), significantly less decay was found among hydrocooled fruit, 6.3 versus 17.5%, whereas in the second comparison (trial 3) more decay developed among the hydrocooled fruit, 51.9 versus 22.5%. Decay incidences among hydrocooled fruit in trial 1 were also high, averaging 27%, but the storage regime featured an accidental warming of the berries to 15°C for 5 days, a temperature that was much more favorable for decay devel-

Table 1. Decay incidence (gray mold and Rhizopus rot) among strawberries (cv. Sweet Charlie) after an 8- or 15-day storage period as affected by method of precooling, addition of chlorine to hydrocooler, and wrapping baskets of berries with a plastic film

			Decay (%)					
			Trial 1		Trial 2		Trial 3	
			Storage period (days)					
Cooling method[a]	Chlorine[b]	Wrap	8[c]	15[d]	8[c]	15[e]	8[c]	15[f]
Hydrocool	–	–	0[g]	12.5	0	7.5	5.0	25.0
	–	+	0	40.0	2.5	5.0	0	62.5
	+	–	0	18.0	2.5	2.5	2.5	47.5
	+	+	2.5	37.5	4.9	10	5.0	72.5
Forced-air (Fa)	NA[h]	–	NA	NA	2.5	17.5	0	10.0
	NA	+	NA	NA	7.5	17.5	0	35.0
Cooling method (Cm)[i]			NS[j]	NS	NS	*	NS	***
Wrap (Wr)			NS	**	NS	NS	NS	***
Cm × Wr			NS	NS	NS	NS	NS	NS
Orthogonal contrasts								
Hydro vs Fa[k]			NS	NA	NS	*	NS	***

[a] Hydrocool method: berries immersed in ice water until pulp temperatures reached 3°C (about 6 min). Forced-air method: berries cooled with moving air until pulp temperatures reached approximately 10 (trial 2) or 7°C (trials 1 and 3) (about 1 h).
[b] Free chlorine concentration was 200 mg/liter at pH 9.0.
[c] 7 days at 1°C and 1 day at 20°C.
[d] 7 days at 1°C, 5 days at 15°C, 2 days at 7°C, and 1 day at 20°C.
[e] 7 days at 1°C, 7 days at 7°C, and 1 day at 20°C.
[f] 14 days at 1°C and 1 day at 20°C.
[g] Means of four 10-fruit replicates.
[h] Not applicable or not tested.
[i] Trial 1 = hydrocooled with or without chlorine in water. Trials 2 and 3 = hydrocooled with chlorine, hydrocooled without chlorine, and forced-air cooled.
[j] *F* test with NS = not significant and *, **, or *** corresponding to $P < 0.05$, 0.01, or 0.001, respectively.
[k] Mean incidence of decay among hydrocooled compared with forced-air–cooled berries.

opment than those used in the other tests. In trial 3, the berries had more harvest-related bruises and were riper and softer than those used in trials 1 and 2. Despite efforts to cull injured fruit prior to the cooling treatments, water-soaked bruises and scrapes on berries were observed immediately after the hydrocool treatment. The water soaking, however, disappeared within 24 h of the treatment.

Wrapping the baskets with plastic film to create a moisture barrier increased decay incidence when the berries developed high average disease incidences. For example, the plastic wrap had no significant effect on decay incidence observed after the 8-day storage regimes or after the 15-day regime in trial 2 (Table 1). However, a significantly higher decay incidence was associated with the wrap after berries in trials 1 and 3 had been stored for 15 days. The magnitude of the decay increase associated with the wrap in trial 3 was similar for hydrocooled and forced-air–cooled berries.

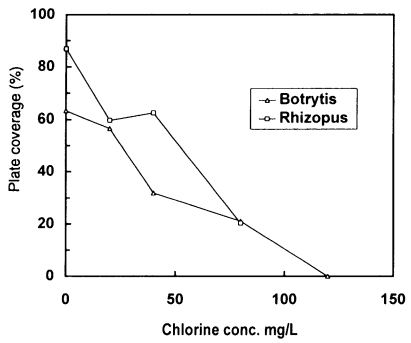

Fig. 1. Percent coverage of potato dextrose agar in 150-mm petri plates by mycelium of *Botrytis cinerea* or *Rhizopus stolonifer* after incubation at 24°C for 48 or 24 h, respectively. Spores were treated with different concentrations of chlorine in water at 2°C (*B. cinerea*) or 5°C (*R. stolonifer*) pH 7.0 for 2 min and then samples were spread over the agar.

Chlorine concentration required to kill spores of *B. cinerea* or *R. stolonifer* in cold water. The development of mycelium from spores spread over PDA in petri plates was used as a presumptive test to find a concentration of chlorine that would kill spores of *B. cinerea* or *R. stolonifer* suspended in cold water within 2 min. Exposure of spore suspensions to water at 2°C (*B. cinerea*) or 5°C (*R. stolonifer*) had no apparent effect on their ability to develop into mycelium (Fig. 1). As free chlorine increased from 10 to 80 mg of chlorine per liter at pH 7, the viability of spores of *R. stolonifer,* measured by their ability to grow over the plates, decreased. With 80 mg of chlorine per liter, growth was observed on three of nine plates.

Within 48 h after plates were spread with spores of *B. cinerea* sampled from aqueous suspensions, fungal growth covered 18.5 to 81.5% of the medium's surface (Fig. 1). Growth developed on five of nine plates spread with samples from the treatment with 80 mg of chlorine per liter, whereas none of nine plates spread with samples from the treatment with 120 mg of chlorine per liter developed fungal growth.

The addition of a surfactant, Tween 80, to the spore suspensions did not statistically affect plate coverage; so, data for the Tween 80 treatments was combined with data from treatments without Tween 80 (Fig. 1). Based on the preceding results, a chlorine concentration of 120 mg/liter at a pH ≤7.0 was used to sanitize water in subsequent tests on the possible inoculation of strawberries during hydrocooling.

Effect of chlorination of hydrocooler baths on gray mold and Rhizopus rot in bruised strawberries. Probable conditions in hydrocooled berries in trial 3 above were simulated by bruising berries intentionally and then hydrocooling them in water containing pathogen spores. Most of the berries hydrocooled in water containing viable spores of *R. stolonifer* or *B. cinerea* were diseased by the end of the respective storage periods (Tables 2 and 3, respectively). Lesions usually originated at the bruises. Nontarget diseases, such as anthracnose caused by *Colletotrichum* spp., were not observed. Diseases found after the respective storage regimes were those caused by the inocula added to the water. For example, only gray mold developed among berries stored for 11 days at 7°C and only Rhizopus rot developed within 2 days at 24°C.

Chlorination of the water in the hydrocooler reduced the incidence of Rhizopus rot from the 99% found when berries were cooled in contaminated water to 7% when the water contained both chlorine and spores (Table 2). Berries cooled in clean water developed 9% Rhizopus rot. The incidence of gray mold averaged 95% when viable spores of *B. cinerea* were added to the water, 42% when both chlorine and spores were included, and 61% when clean water was used (Table 3). Thus, decay resulting from the inoculation of berries during the immersion hydrocooling was eliminated by chlorination of the hydrocooler.

Decay resulting from natural inoculum on the berries was inconsistently affected by the addition of chlorine to the water. For example, the incidence of Rhizopus rot averaged nearly 11% after the clean water plus chlorine treatment, 8% for all chlorine treatments, and 9% in the controls (Table 2). Because the chlorine had no effect on the incidence of Rhizopus rot unless inoculum was added to the water, there was a significant ($P < 0.01$) interaction between the chlorine and inoculum treatments. By contrast, the naturally occurring incidence of gray mold among hydrocooled berries was reduced when the water was chlorinated. Decay incidence averaged 61% among fruit cooled in clean water and 43% when chlorine was added to water with or without spores of *B. cinerea* (Table 3). The difference in disease incidence in the chlorine plus clean water versus clean water alone treatments was significant at $P = 0.0051$. Thus, some of the *B. cinerea* propagules that were naturally present on the berries were vulnerable to chlorine.

Table 2. Decay incidence among hydrocooled fruit of three strawberry cultivars as affected by presence of spores of *Rhizopus stolonifer* and chlorine in the water[a,b]

		Decay incidence (%)			
Chlorine[c]	Inoculum[d]	Chandler	Oso Grande 1	Oso Grande 2	Sweet Charlie
–	–	0[e]	13	5	13
+	–	8	15	15	5
–	+	100	100	100	98
+	+	0	13	18	8
Chlorine (Cl)[f]				****	
Inoculum (inoc)				****	
Cl × inoc				****	
Block[g]				*	
Orthogonal contrasts					
Cl vs no Cl (inoc treatments[h])				****	
Cl vs no Cl (no inoc treatments[i])				NS	

[a] Strawberries at 24°C immersed for 6 min in 1°C water and stored at 24°C for 2 days.
[b] Harvest dates for Oso Grande 1, Sweet Charlie, Chandler, and Oso Grande 2 were 26 February, 28 February, 2 March, and 14 March 1994, respectively.
[c] 120 mg of free chlorine per liter at pH 6.5.
[d] 1×10^4 spores/ml.
[e] Means of four 10-fruit replications.
[f] *F* test with NS = not significant and * and **** corresponding to $P \leq 0.05$ and 0.0001, respectively.
[g] Cultivar harvest date.
[h] Effect of chlorine within inoculum treatments.
[i] Effect of chlorine within no-inoculum treatments.

DISCUSSION

Hydrocooling has promise as a method to cool strawberries rapidly in a continuous process. Hydrocooled berries remain firmer, have better color, and suffer less water loss during storage compared with forced air-cooled berries (8,9,25,26). Hydrocooling strawberries provides additional benefits over alternative cooling methods, e.g., more rapid cooling, cleaning the berries, removing pesticide residues, and, per-

haps, removing inoculum from berry surfaces. The apparently widespread belief that harvested strawberries will be injured and/or will decay if exposed to hydrocooling (5,15,20,27) is not supported by reports on hydrocooling strawberries (8,9,25,26). In tests reported here, with high-quality berries (trial 2), hydrocooling was not associated with increased decay when compared with forced-air cooling. However, the hydrocooling of poor quality berries did lead to excessive decay (trial 3). With respect to the effect of hydrocooling on fruit quality, there was no evidence in any of three different hydrocooling trials that berries were injured either by water or by chlorinated water. On the contrary, hydrocooled fruit, compared with forced-air–cooled fruit, appeared more resistant to certain types of injury, were firmer, and had a better color (more like freshly harvested strawberries) (8).

Hydrocooled berries may experience fewer postharvest decays than berries cooled by other methods because of a slower loss in berry firmness during storage (8,9,25,26), or because a portion of the inoculum on the berries may have been washed off. Hortynski (13) noted that berries with greater firmness were more resistant to infection by *B. cinerea* than softer ones; Maas (17) observed that cultivars that maintain fruit firmness longer have greater resistance to infection by *B. cinerea* than those that soften more quickly. The cleansing of berry surfaces during hydrocooling may also lead to reduced decay development. Washing has been reported to remove up to 90% of the microbes on the surface of fresh fruits and vegetables (10). Removal of surface-borne inoculum as an explanation of decay reductions associated with hydrocooling berries is consistent with evidence from water chlorination tests presented here, in which the chlorination of clean water used to hydrocool berries reduced the naturally occurring incidence of gray mold. The latter observation is evidence that spores of *B. cinerea* can be found on berry surfaces and are likely to be washed into the water. Alternative explanations—that chlorine eliminated some latent infections, spores embedded in wounds, or structures attached to fruit surfaces—are not consistent with the antimicrobial activity of chlorinated water (2,6).

The high decay incidence observed here among certain groups of hydrocooled fruit is a source of concern regarding use of this cooling method on strawberries. In trial 3, roughly twice as much decay developed among hydrocooled fruit compared with air-cooled fruit, contrary to the result found in an earlier test (Table 1). The high disease incidence in hydrocooled fruit in trial 3 may be related to the use of fruit that were prone to decay. Berries obtained for this trial were harvested by technical assistants from a commercial field after it had been opened to "U-pick." Such fields are not routinely treated with fungicide applications for fruit rot control. Moreover, large numbers of diseased and over-ripe berries would be accumulating in the field. High numbers of pathogen propagules and latent infections could be expected among berries harvested from such fields. When the harvested berries arrived at the Postharvest Laboratory, a high incidence of brusing was observed (7). Attempts to cull damaged fruit prior to the cooling treatments were only partially successful as bruises, visible as water-soaked spots, were evident on berries immediately after hydrocooling.

The two factors associated with hydrocooling strawberries that appeared likely to promote the development of postharvest decays were free moisture left on berry surfaces and inoculation by contact with contaminated water. Water left on the cooled berries did not appear to promote decay development in the tests reported here. Water droplets disappeared from berry surfaces within 24 h of treatment. The wrapping of baskets of both hydrocooled and forced-air–cooled berries with plastic film to slow moisture loss led to either no change or increased postharvest decay. The film wrap did not promote decay development more when applied to berries with wet surfaces (from the hydrocooler), compared with those with dry surfaces (from the forced-air cooler). The film was an effective moisture barrier, however, since fruit in wrapped baskets lost weight at a slower rate during storage and appeared fresher at the end of the respective storage treatments than did those in unwrapped baskets (8). If residual surface moisture had contributed to decay development, then the wrap, by delaying the drying of water droplets from wet berries, should have affected incidence more when applied to hydrocooled fruit.

Hydrocooled strawberries may be inoculated by postharvest pathogens as they are cooled. Rose and Gorman (26), Goble and Cooler (9), and Ferreira et al. (8) all reported that berries consistently or often gained weight as they were cooled. Ferreira et al. (8) observed weight increases up to 2% of initial fresh weight for hydrocooled fruit along with occasional, though temporary, water soaking at wounds. These observations are evidence that the berries were infiltrated with hydrocooler water. Extensive postharvest decays in tomatoes (1,4) and an increase in soft rot potential in potato tubers (3) have been associated consistently with the infiltration of these products by pathogen-contaminated wash water. Infiltration of inoculum-contaminated water into harvest-related wounds could explain the high decay incidence observed here among hydrocooled fruit in trial 3 (Table 1). Moreover, the high disease incidence that developed in berries hydrocooled in contaminated water here is consistent with an infiltration of berry tissues with water containing pathogen structures.

Water chlorination did not reduce postharvest decays in the initial tests on hydrocooling strawberries. The chlorine concentration, 200 mg/liter, was more than adequate to kill unprotected fungal spores, particularly during a 6-min exposure period (2,6,16,23). The lack of efficacy is likely to have been caused by the high pH and low temperatures of these solutions, which would have greatly restricted the activity of the chlorine (2,6). On the other hand, water chlorination did not prevent decay development in tomato fruit that had been contaminated with *Erwinia carotovora* subsp. *carotovora* and then infiltrated with chlorinated water at 26°C and pH 6.8

Table 3. Decay incidence among hydrocooled strawberry fruit of three cultivars as affected by spores of *Botrytis cinerea* and chlorine in the water[a,b]

Chlorine[c]	Inoculum[d]	Decay incidence (%)		
		Chandler	Oso Grande	Sweet Charlie
–	–	43[e]	90	50
+	–	20	65	48
–	+	88	100	97
+	+	35	58	33
Chlorine (Cl)[f]			**	
Inoculum (inoc)			****	
Block[g]			****	
Cl × inoc			****	
Orthogonal contrasts				
Cl vs no Cl (inoc treatments[h])			****	
Cl vs no Cl (no inoc treatments[i])			*	

[a] Strawberries at 24°C immersed for 6 min in 1°C water and stored at 7°C for 11 days.
[b] Sweet Charlie, Chandler, and Oso Grande were harvested 18 March, 18 March, and 27 March 1994, respectively.
[c] 120 mg of free chlorine per liter at pH 6.5.
[d] 1×10^4 spores/ml.
[e] Means of four 10-fruit replications.
[f] *F* test with *, **, and **** corresponding to $P \leq 0.05$, 0.01, and 0.0001, respectively.
[g] Cultivar date.
[h] Effect of chlorine within inoculum treatments.
[i] Effect of chlorine within no inoculum treatments.

to 9.6 (1). However, in tests reported here on the chlorination of hydrocooler water that had been contaminated with pathogen spores, a chlorine concentration of 120 mg/liter at pH 6.5 protected bruised strawberries from inoculum suspended in the water. At this pH level, most of the free chlorine in the solutions would exist as hypochlorous acid, which is extremely active against microbes (6). By contrast, in the initial hydrocooling trials the pH of the chlorine solutions was 9.0; at that level, 97% of the unreacted chlorine would be OCl^-, which is not very active against microbes (6). Thus, when hydrocooling strawberries, use of a proper chlorine concentration and pH level appears to be necessary for adequate sanitation of the water.

Decay concerns associated with the probable infiltration of strawberries by water from hydrocoolers should not prevent this cooling method from being adopted by the industry. Decay incidences found in hydrocooled berries here after an 8-day storage regime were similar to those in forced-air–cooled berries and were equal to or less than the 5% allowed by grade standard in 12 different treatments. The berries used in these tests were likely more decay prone than standard commercial berries because the delay between harvesting and cooling included transportation from field to the Postharvest laboratory (approximately 2 h) plus a 6-h preconditioning treatment. With a proper interval between harvest and hydrocooling, much less than the average 2.1% decay observed here among hydrocooled berries that had been stored for 8 days would be expected. If the water is properly sanitized, the berries are of good quality with relatively few bruises, and the cooled berries are subsequently stored at ideal temperatures (0 to 1°C), the decay risk associated with hydrocooling strawberries appears minimal. Additional comparisons between hydrocooled and forced-air–cooled fruit are needed, however, to clarify the relative decay incidences when fruit are cooled and stored under commercial conditions, which usually feature less than ideal storage temperatures (3 to 5°C).

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