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Relationship between Preharvest Factors and the Incidence of Storage Disorders in 'Fuji' Apples during CA Storage

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Abstract. This study was carried out to evaluate the effect of pre-harvest factors on fruit quality and the incidence of storage disorders in 'Fuji' apple during CA storage. Incidence of storage disorders varied, depending on the growing regions, field conditions, and altitude of the orchards. Results indicated that fruit maturity may play a crucial role in the incidence and severity of flesh browning and watercore. The incidence of these storage disorders increased with fruit maturity until 180 days after full bloom (DAFB). In addition, occurrence of watercore was correlated with the incidence of flesh browning during CA storage. The incidence of flesh browning was positively correlated with the sum of the diurnal temperature range from September through October and amount of precipitation from August to October in 1996-1999 growing years. These results suggested that 'Fuji' apple should be harvested no later than 180 DAFB because the late harvested fruits were prone to development of watercore which was correlated with the incidence of flesh browing during CA storage in Korea.

***Additional key words*:** field conditions, flesh browning, harvest date, watercore

Introduction

Controlled atmosphere (CA) storage is the most common storage system for apple fruit (Smock, 1979). Although storage conditions vary, dependent upon the cultivar, growing conditions, and harvest maturity, apple fruit are generally stored at 1-3℃ with 1.5 kPa O_2 and 3 kPa CO_2 partial pressure (Kupferman, 2003; Smock, 1979). Fruit quality and storage disorders during CA storage are mainly affected by harvest date and also the O_2 and CO_2 partial pressure imposed during storage (Lau, 1988; Yiping et al., 2001). Flesh browning disorder is one of the most serious storage disorders caused by chilling injury during storage, reducing market value and shelf life. It is known that flesh browning occurs more prevalently as harvest time is delayed in 'Braeburn' (Burmeister and Dilley, 1995; Meheriuk, 1977; Smock and Blanpied, 1963) and 'Fuji' apple (Hwang et al., 1998; Park et al., 1997). However, it still remains unclear what the metabolic mechanisms enhance the incidence of flesh browning disorder incidence in later harvests, although it has been mentioned that the risk of flesh browning might be aggravated by the accumulation of ethanol and acetaldehyde in fruit tissue, the reduction of gas diffusion, and the enhanced susceptibility to low O_2 and high CO_2 partial pressure (Argenta et al., 2002; Park and Lee, 1991; Park et al., 1997). In addition, watercore was highly correlated with the risk of storage disorders during CA storage (Fukuda, 1984; Hwang et al., 1998). 'Delicious' and 'Jonathan' apples were highly susceptible to watercore, thereby enhancing the risk of flesh browning disorder during CA storage (Clijsters,

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1965; Smagula et al., 1968). Thus, the incidence and severity of flesh browning was different in watercored 'Fuji' apples, depending on CA regimes (Bowen and Watkins, 1997; Harker et al., 1999). Furthermore, it was suggested that watercored fruits may develop flesh browning as a result of the accumulation of ethanol and acetaldehyde levels (Argenta et al., 2002). However, there was no direct evidence of the relationship between watercore and flesh browning during CA storage (Park et al., 1997). Therefore, the objective of this work was to investigate the effect of pre-harvest factors and growing conditions on the incidence of storage disorders during CA storage in 'Fuji' apple, a major cultivar in Gyeongsangbuk-do, Korea.

Materials and Methods

Fruit Harvest and Geographical Characteristics of Apple Orchards

'Fuji' apple was harvested 3-5 times prior to 180 DAFB from experimental fields of Apple Research Station at Gunwi, Gyeongbuk, Korea in 1996-1999 and 2002 for CA storage experiment. In 1998, two apple orchards were selected at Gunwi and Andong located in a field on a plain located over 400 meters above the sea level. In 1999, one 'Fuji' apple orchard from Gunwi and Andong was chosen for the evaluation of fruit maturity and flesh browning. In 2002, one orchard from each Gunwi and Uiseoung at mid-Gyeoungbuk, Youngju and Moonkyung at northern-Gyeoungbuk was used to investigate the relationship between O_2/CO_2 condition and physical disorders during CA storage.

Fruit Storage

In the experiments carried out in 1998 and 1999, 'Fuji' apples were transferred to a cold room (0-1℃) immediately following harvest, held for two days, then placed at 2-3 kPa O_2/1-2 kPa CO_2 partial pressure for seven months. In the experiments of 2002, the fruits were stored for two months at 0-1℃ and moved to high CO_2 (1-2 kPa O_2/1-2 kPa CO_2) or low CO_2 (1-2 kPa O_2/lower than 1 kPa CO_2) CA storage chambers for seven months.

Evaluation of Harvest Maturity Characteristics

To evaluate maturity of the harvested fruits, starch iodine index, Hunter's a value, and watercore incidence were measured. Starch staining with iodine was measured on 10 fruit per replicate on the harvest date using a visual rating in 5 stages from 5 (unripe) to 1 (ripe) after iodine treatment of cut surface of fruits. The Hunter's a value was measured using a chromameter (CR 100, Minolta, Ramsey, NJ). Three readings were taken around the equatorial region of each fruit and then averaged (McGuire, 1992). Growing climate was evaluated to reveal any relationships between weather conditions and storage disorders. Fruits harvested in 1998 were examined for carbon dioxide production, ethylene production, and internal ethylene concentration (IEC). Carbon dioxide and ethylene production were determined using a Hewlett-Packard 5890 gas chromatograph (Hewlett-Packard, Wilmington, DE), equipped with activated carbon column (0.92 m × 2 mm) and a thermal conductivity detector (TCD) for carbon dioxide, and with active alumina column (2 m × 2 mm) and flame ionization detector for ethylene. Gas samples (1 mL) were withdrawn from the core cavity of each apple fruit for IEC measurements. To measure ethylene production and respiration rate, fruits were placed individually into sealed 1.6 L plastic containers and then 1 mL of gas samples were withdrawn from the head space of sealed plastic containers after incubation for 1 h.

Assessment of Storage Disorders

Watercore was evaluated by a visually scoring symptoms on the cut surface of the equatorial region [0 (no symptom) to 5 (severe symptom)] (Bowen and Watkins, 1997). Then flesh browning and cavity formation were assessed by cutting at least three times equatorially. Flesh browning and cavities detected are presented as percentage (Kweon et al., 1998).

Statistical Analysis

Analyses of variance and Duncan's multiple range test were performed using the Statistical Analysis System program (SAS Institute, Cary, NC) and results significant at $P = 0.05$ are discussed. The correlation coefficients between incidence of flesh browning and climatic factors were calculated using the correlation coefficient procedure (PROC CORR) of SAS (SAS Institute, Cary, NC).

Results and Discussion

Table 1 shows the incidence of CA-induced storage disorders according to the location of apple orchards in Gyeongsangbuk-do, Korea. The incidence of flesh browning and cavity formation was different depending on the altitude of orchards within the same region during the 1998 growing season. Orchards located over 400 meters of altitude had a higher incidence of flesh browning in both Gunwi and Andong (Table 2). In comparison to the incidence of storage disorders in Andong and Gunwi orchards, the hilly orchard in Andong had more severe watercore incidence to 3.1% and caused higher browning to 12% than plain orchard in Gunwi (Table 3). Lau (1998) also reported similar results, that higher altitude with lower temperature caused more

Table 1. Experimental details including growing year, orchard location, and CA storage regime of 'Fuji' apples.

Growing year	Region	Harvest date	No. of orchard	CA gas condition	
				O_2 (kPa)	CO_2 (kPa)
1998	Gunwi	Oct. 20	3	2-3	1-2
	Andong	Oct. 21	2		
1999	Gunwi	Oct. 22	1	2-3	1-2
	Andong	Oct. 21	1		
2002	Gunwi	Oct. 27	1	1-2	1-2
	Uiseoung	Oct. 27	1		or
	Youngju	Oct. 28	1		< 1
	Moonkyung	Oct. 28	1		

Table 2. Effect of orchard location on the incidence of storage disorders of 'Fuji' apple in Gunwi and Andong in 1998.

Region	Orchard	Browning (%)	Cavity (%)	Total (%)
Gunwi	Orchard I[z]	8	4	12
	Orchard II[z]	6	2	8
	Orchard III[y]	20	5	25*
Andong	Orchard I[z]	25	3	28
	Orchard II[y]	34	6	40*

[z]Orchard located in plain field.
[y]Orchard located in over 400 m altitude.
[*]Significant at P = 0.05.

Table 3. The relationship between fruit maturity and incidence of storage disorders of 'Fuji' apple during seven months CA storage in 1999.

Orchard region	Harvest maturity		Flesh browning (%)	Cavity (%)	Total (%)
	Harvest date	Watercore index			
Gunwi (plain)	Oct. 22 (180DAFB[z])	2.5[y]	6	2	8 b[x]
Andong (hill)	Oct. 21 (176DAFB)	3.1	9	3	12 a

[z]DAFB: Days after full bloom.
[y]Watercore index: 5 (severe) - 0 (no symptom).
[x]Mean separation within a column by Duncan's multiple range test at P = 0.05.

Table 4. Effect of CO_2 partial pressure on the incidence of flesh browning in 'Fuji' apple during CA storage in 2002. Fruits were harvested on Oct. 27 at Gunwi and Uiseoung orchards, and Oct. 28 at Youngju and Moonkyung orchards.

CA gas condition (kPa)		Incidence of browning disorder (%)			
O_2	CO_2	Gunwi	Uiseoung	Youngju	Moonkyung
1-2	1-2	2.5	0	0	1.2
1-2	< 1	0	0	0	0.5

incidence of flesh browning disorder than relatively low-lying 'Braeburn' apple orchards in New Zealand.

Along with the impacts orchard altitude and topography had on the incidence of storage disorders, the effects of orchard location were also investigated. While fruit from Youngju and Uiseoung did not have any symptoms of flesh browning disorders, fruit from Gunwi and Moonkyung had 0-2.5% and 0.5-1.2% of flesh browning incidence rate, respectively. When CO_2 partial pressure was elevated to 1-2 kPa, the incidence rate of flesh browning also rose to 2.5% and 1.2% (Table 4). Since the rate of gas permeance is sensitive to the reduced O_2 and elevated CO_2 partial pressure, decreased gas permeance may contribute to an elevated risk of flesh browning during CA storage (Park and Lee, 1991). Thus, the incidence and severity of storage disorders in 'Fuji' apple appeared to be associated with the difference of tissue gas permeance which was related to orchard variation. Moreover, the incidence of flesh browning and cavities were

Table 5. Effect of harvest maturity on the fruit quality characteristics of 'Fuji' apple harvested from Gunwi during CA storage from 1996 to 1999.

Growing season	Harvest Date	Days after full bloom	Maturity characteristics			
			Starch index[z]	Watercore incidence (%)	Hunter's *a* value	Incidence of browning (%)
1996	Oct. 15	165	2.9 a[y]	12 c	17.3 b	0
	Oct. 22	172	2.1 a	18 c	17.5 b	0
	Oct. 29	179	2.0 a	60 b	20.9 a	8
	Nov. 5	186	1.0 b	87 ab	19.9 a	17
	Nov. 12	191	1.0 b	96 a	20.3 a	67
1997	Oct. 15	172	2.8 a	20 b	20.3 c	0
	Oct. 22	179	1.8 b	40 ab	19.3 c	16
	Oct. 29	186	1.3 ab	57 a	22.3 b	18
	Nov. 5	193	1.0 b	57 a	24.2 a	16
	Nov. 12	200	1.0 b	60 a	22.4 b	34
1998	Oct. 9	170	2.3 a	8 c	18.0 b	0
	Oct. 19	180	1.5 b	35 b	20.4 a	12
	Oct. 29	190	1.0 c	48 a	22.3 a	26
1999	Oct. 13	171	2.3 a	10 c	19.4 b	2
	Oct. 22	180	1.5 b	35 b	24.5 a	2
	Nov. 1	190	1.0 c	58 a	25.8 a	8

[z]Starch iodine index: 5 (unripe) - 1 (ripe).
[y]Mean separation within columns by Duncan's multiple range test at P = 0.05.

typical symptoms of storage disorders in CA stored 'Fuji' apple (Argenta et al., 2002; Park et al., 1997). Watercore may be involved in flesh browning development and may worsen cavity development. Furthermore, Fukuda (1984) reported that sorbitol accumulation in cortex tissues inhibited gas diffusion and causing cell death. Harker et al. (1999) also noted that sorbitol accumulation provoked fermentation and cell breakdown. Therefore, it has been assumed that losing water from injured area may contribute to the development of cavities towards the end of long term storage (Hwang et al., 1998; Kweon et al., 1998).

In order to elucidate the relationship between the harvest date and storage disorder incidence, fruits were harvested from the same orchard in Gunwi through 1996-1999 and 2002 (Table 5). Fruit maturity was different based on year-to-year variation. Although fruit were harvested at the same date, DAFB were different. However, starch iodine index had very similar result as 1.0 at the beginning of Nov., which indicated that fruit were mature. No strong correlation between the starch index at harvest and the incidence of flesh browning was found (r = 0.226, data not shown). Incidence of watercore was first detected when fruit maturity had advanced, although watercore severity was different among growing years. Severe watercore was recorded in 1996, which had the latest flowering. In this year, fruit harvested at 179 DAFB had 60% of watercore, compared with 96% on 191 DAFB. These results suggest that 'Fuji' apple should be harvested no later than 180 DAFB to minimize flesh browning incidence during long term CA storage in Korea. Regardless of similar harvest dates among years, severity of watercore was different due to climatic factors (Tables 5 and 6). Flesh browning was highly correlated with the diurnal temperature range from Sept.-Oct. and Oct., and precipitation of Aug.-Oct. and Sept.-Oct. in 1996-1999, while it did not have any relationship with average air temperature or maximum or minimum air temperature among growing years (Table 6). Additionally, flesh browning incidence was highly correlated with watercore (r = 0.756, data not shown), fruit maturity, and harvest time. Hunter's a value did not change at 179 DAFB in 1996, 186 DAFB in 1997, 180 DAFB in 1998, 1999, and 185 DAFB in 2002 indicating red blush might be less indicative of storage disorder risk.

In this experiment, flesh browning increased with increasing harvest date indicating mature fruit were more susceptible to low O_2 and high CO_2 partial pressure (Argenta et al., 2002; Lau, 1998; Yiping et al., 2001). Thus, it is important to calculate exact DAFB for the apple harvest in order to minimize the development of storage disorders during long-term CA storage of 'Fuji' apple. Furthermore, fruit respiration rate plays a pivotal role in governing fruit storability at

Table 6. Correlation coefficients between flesh browning incidence in 'Fuji' apples and climatic factors in 1996-1999.

Climatic factors	Corresponding period						
	Full bloom to Oct.	May to Oct.	Jun. to Oct.	Jul. to Oct.	Aug. to Oct.	Sept. to Oct.	Oct.
Cumulative air temp.	0.730	0.220	0.405	0.300	0.382	0.444	0.049
Average air temp.	0.284	0.008	0.165	0.161	0.242	0.228	0.096
Max. air temp.	0.082	0.069	0.098	0.031	0.306	0.234	0.586
Min. air temp.	0.008	0.243	0.661	0.489	0.510	0.511	0.404
Diurnal temp. range[z]	0.157	0.516	0.579	0.474	0.689	0.782*	0.814*
Rainfall	0.593	0.639	0.597	0.529	0.831*	0.620*	0.673

[z]Maximum temperature - minimum temperature.
*Significant at P = 0.05.

harvest and is, thus, related to the senescence rate of apples after harvest (Romani, 1984). The respiration rate of 'Fuji' apple was lower during CA storage than in air storage (Fig. 1A). Respiration rate steadily increased right after harvest when in air storage, while little change occurred in CA storage until April with slight increase as harvest maturity increased. Smagula et al. (1968) also noted that CO_2 partial pressure increased after reaching a certain O_2 partial pressure threshold provoking fermentation and alcohol and acetaldehyde accumulation ostensibly leading to flesh browning. Ethylene production rate was 0.10-0.18 $\mu L \cdot kg^{-1} \cdot h^{-1}$ at harvest and increased dramatically by cold storage, compared to CA storage (Fig. 1B). However, no difference in ethylene production among the harvest times was noted. IEC levels responded similarly to ethylene evolution (Fig. 1C). Results reveal that the geological location of apple orchards may be associated with flesh browning development as well as harvest date.

In conclusion, the incidence of storage disorders, such as flesh browning and cavity development, could be differentially affected by not only orchard variation and harvest time but also CA imposed storage regimes and climatic factors. As fruit maturity was advanced, the watercore incidence was also increased hastening flesh browning and cavity development in the worst cases.

These results suggested that 'Fuji' apple should be harvested no later than 180 DAFB because the late harvested fruits were prone to development of watercore which was correlated with the incidence of flesh browing during CA storage in Korea.

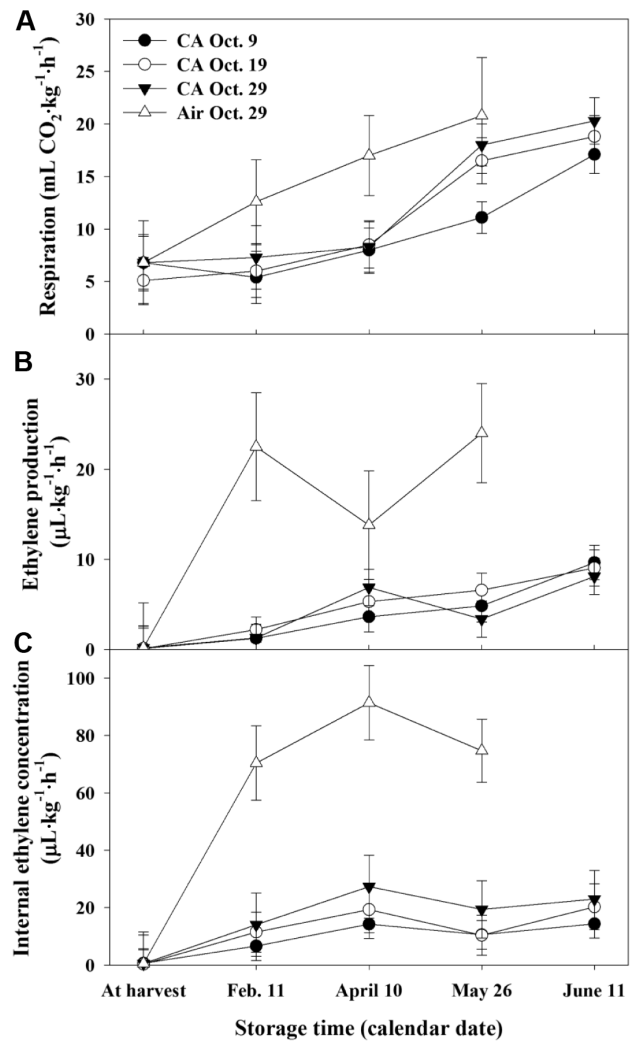

Fig. 1. Respiration (A), ethylene production (B), and internal ethylene concentration (C) of 'Fuji' apples during CA or air storage at Gunwi in 1998. Data are means ± SD (n = 10). CA storage condition was 2-3 kPa O_2 and 1-2 kPa with 0-1℃. Air storage was 0-1℃. Harvest date was Oct. 9, Oct. 19 and Oct. 29.

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