Prohexadione–calcium Inhibits Shoot Growth but Reduces the Efficacy of Gibberellin A4 + A7 in Suppressing ‘Stayman’ Apple Cracking

Stephen S. Miller¹

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SUMMARY. The ‘Stayman’ apple (*Malus×domestica*) is a high-quality apple with good fresh-fruit and processing characteristics. Trees are of moderate to high vigor where it is grown in large numbers in the mid-Atlantic region of the United States. However, ‘Stayman’ is prone to skin cracking, which in some seasons can result in losses that exceed 60% to 80% of the crop. A series of experiments was conducted between 1997 and 2001 to examine the effect of prohexadione–calcium (PCa) and a mixture of gibberellins A4 plus A7 (GA₄₊₇) on shoot growth and cracking in ‘Stayman 201’ apple. PCa consistently reduced terminal shoot growth when applied in two or three sprays between petal fall (PF) and PF + 6 weeks [May and June (postbloom)]. PCa applied postbloom combined with three or four preharvest (July and August) PCa applications reduced the growth of water sprouts. The level of ‘Stayman’ fruit cracking varied with year, but in three of five experiments conducted from 1997 through 2001, five biweekly GA₄₊₇ sprays applied alone preharvest reduced the percentage of cracked fruit at harvest. With only a few exceptions, spraying with PCa increased fruit cracking. When GA₄₊₇ was applied to trees previously treated postbloom with PCa, the percentage of cracked fruit was often reduced, but not always, and generally not to the same level as that in non-PCa-treated trees. Fruit cracking was increased compared with the untreated control when a spray adjuvant was included with the postbloom PCa spray. PCa or GA₄₊₇ had no effect on yield or fruit weight at harvest. The results of this study suggest caution in the use of PCa to suppress shoot growth in bearing ‘Stayman’ apple trees because of the potential for increased fruit cracking, which may be only partially reversed by the application of GA₄₊₇.

‘Stayman’ apple is a very old cultivar (Beach et al., 1905) prized for its culinary and processing qualities (Dreiling and Williams, 1962). It has been grown in virtually all apple growing regions of the United States from the early 1900s, but more recently, the bulk of production has been associated with the mid-Atlantic apple growing region. ‘Stayman’ apples exhibit good fruit size, regular cropping, good storage characteristics, and a finely textured, sprightly flavored flesh. In

the fresh-fruit market, ‘Stayman’ often receives a premium price (D. Rice, personal communication), making it an attractive cultivar to growers. Despite all its good qualities, ‘Stayman’ is susceptible to fruit cracking. Characterized by large cracks that develop in the skin and often extend deep into the cortex tissue, cracking can result in preharvest fruit losses of 25% to 50% or even more in some years (Byers and Carbaugh, 1995; Gardner and Christ, 1953; Miller, 1990).

Verner (1935) conducted extensive studies on the cracking disorder in ‘Stayman’ and concluded that a number of factors were associated

with cracking, but there was no one single causal factor responsible for the disorder. Various cultural management practices to reduce cracking have been investigated (Opara et al., 1997) and recommendations made (Baughner et al., 1995; Byers et al., 1990; Gardner and Christ, 1953; Opara, 1996; Stiles et al., 1959), but few, if any, of these methods have consistently reduced cracking except the application of plant growth regulators (Byers and Carbaugh, 1995; Byers et al., 1990; Costa et al., 1983; Miller, 1990). Sullivan and Widmoyer (1970) reported that a single spray of daminozide (Alar-85; Crompton/Uniroyal Chemical, Middlebury, CT) at 2000 ppm reduced cracking of ‘Stayman’ apples. Costa et al. (1983) found that four sprays of daminozide at 1000 ppm applied between 42 and 109 d after full bloom significantly reduced cracking in ‘Stayman Red’ apples. Four sprays at 2000 ppm reduced cracking, but also reduced fruit weight and yield.

A single spray of 1000 ppm daminozide applied on 27 July reduced the percentage of cracked ‘Stayman’ apples from 58% to 35% (Byers et al., 1990). In the same study, four weekly sprays of gibberellins A4 plus A7 (GA₄₊₇) at 20 ppm beginning 27 July reduced cracking from 58% to 21%. In a later study on ‘Stayman’ showing severe cracking (controls with 95% cracked fruit), five sprays of 10 ppm GA₄₊₇ alone or combined with one spray of 1000 ppm daminozide reduced cracking by only ≈15%. When Byers et al. (1990) added naphthaleneacetic acid (20 ppm) and pinolene (Vapor-Gard; Miller Chemical & Fertilizer Corp., Hanover, PA) (5 ppm) to the GA₄₊₇ plus daminozide spray solution, cracking was reduced from 95% to 27%.

Miller (1990) reported that four sprays of GA₄₊₇ applied at either 20 or 50 ppm beginning in early July were

U.S. Department of Agriculture, Agricultural Research Service, Appalachian Fruit Research Station, 2217 Wiltshire Road, Kearneysville, WV 25430

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¹Research Horticulturist. E-mail: stephen.miller@ars.usda.gov.

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	ha	2.4711
3.7854	gal	L	0.2642
9.3540	gal/acre	L·ha ⁻¹	0.1069
2.5400	inch(es)	cm	0.3937
28.3495	oz	g	0.0353
0.0749	oz/100 gal	g·L ⁻¹	13.3526
1	ppm	mg·L ⁻¹	1
6.8948	psi	kPa	0.1450

very effective in reducing 'Stayman' cracking even under severe conditions in West Virginia. A study of five concentrations over a range of 0 to 50 ppm GA₄₊₇ produced a curvilinear response; cracking was reduced at 25 and 50 ppm (Miller, 1990). Unrath (1991) in North Carolina reported that five sprays of GA₄₊₇ applied at 50 ppm at 3-week intervals reduced 'Stayman' cracking by 69% to 82% compared with controls. The proprietary mixture of GA₄₊₇ (ProVide; Valent BioSciences Corp., Libertyville, IL) received registration from the U.S. Environmental Protection Agency for suppression of 'Stayman' apple cracking in 1990. Current recommendations suggest three to six consecutive sprays of ProVide 10 SG at 100 to 200 g/100 gal per acre applied at 14- to 21-d intervals beginning 3 weeks before cracking normally appears (Valent BioSciences Corp., 2005).

The 'Stayman' apple tree is a moderately vigorous to vigorous cultivar. The growth suppressant prohexadione-calcium (PCa) (Apogee; BASF Corp., Agricultural Products Group, Research Triangle Park, NC) has demonstrated excellent shoot growth control in a number of apple cultivars (Greene, 1999; Miller, 2002; Rademacher et al., 2004; Schupp et al., 2001) and would seem a likely candidate to control shoot extension growth in 'Stayman'. PCa inhibits GA metabolism by blocking the conversion of the inactive GA₂₀ to the active GA₁, thereby reducing the supply of active GA available for cell elongation (Evans et al., 1999). The question arises, given that PCa is an antigibberellin, will the application of Apogee affect the efficacy of GA₄₊₇ applied to reduce 'Stayman' cracking? The objective of the current study was to examine the efficacy of PCa and GA₄₊₇ on shoot growth and the incidence of fruit cracking in the 'Stayman' apple.

Materials and methods

To examine the objective, a group of experiments was conducted between 1997 and 2001 in bearing 'Stayman' apple trees growing at the Appalachian Fruit Research Station (AFRS), Kearneysville, WV, or in a commercial orchard near Kearneysville. The strain used in all experiments was 'Stayman 201'. All sprays

were applied between 0600 and 0830 HR to facilitate maximum absorption. Sprays were applied at 100 psi with a handgun piston pump sprayer to obtain complete coverage of foliage and fruit to the point of drip. PCa treatments in 1997 and 1998 were applied as a dilute spray at a given concentration. In the 1998 experiment and in all subsequent experiments, ammonium sulfate (AMS) (spray grade) was included as a water conditioner on an equal weight basis with PCa. Beginning in 1999, the final dose for PCa was determined from a specified rate of formulated product in ounces [Apogee 27.5 DF (27.5% a.i. dry flowable formulation)] per 100 gal of spray solution adjusted for the calculated tree-row-volume (TRV) (Sutton and Unrath, 1984) in 100 gal/acre. In all experiments, GA₄₊₇ was applied using the proprietary material ProVide (the liquid formulation) supplied by Valent BioSciences Corp. GA₄₊₇ was applied dilute in five sprays at a given concentration at 2-week intervals beginning approximately 1 July. In each case, except for Expt. 1 (described subsequently and in Table 1), the first two GA₄₊₇ sprays were applied at a concentration of 37.5 ppm and the final three sprays were applied at a concentration of 25 ppm.

Trees were monitored weekly for signs of fruit cracking from 1 Aug. until harvest (approximately 10 Oct.). Cracked fruit were removed and counted as they appeared. At harvest, all fruit were removed and counted and the total percentage of fruit cracked for the season was calculated. In all but Expt. 2, the length of the current season's shoot growth was measured in November on 10 to 20 terminals selected at random on the periphery of the canopy and used to calculate mean terminal shoot growth. Total yield was determined by harvesting all fruit from individual trees and mean fruit weight determined by measuring a minimum of 50 fruit per tree (except for Expt. 2). Data from each experiment were analyzed using a one- or two-way analysis of variance (ANOVA), as appropriate, and treatment means separated by Fisher's protected least significant difference at $P \leq 0.10$. A check of residuals indicated that a transformation of the percentage data was not appropriate or necessary for any of the

variables in any of the experiments. In Expt. 2, data were subjected to a two-way ANOVA and main treatment effects separated using contrast statements.

EXPT. 1. The trees selected were on 'Malling Merton.111' (MM.111) rootstock and beginning their seventh leaf in the orchard. All trees were dormant pruned before the application of treatments in May 1997 and were characterized as highly vigorous. PCa was applied as BAS 125 10W (10% a.i. dry flowable formulation) with the nonionic adjuvant Regulaid (2-butoxyethanol, poloxalene, monopropylene glycol; Kalo, Overland Park, KS) included at 0.03% (v/v). Sprays were designated as either a postbloom (applied in May or June) or a preharvest (applied in July and Aug.) spray, depending on the period in which it was applied. The concentration for individual spray applications and the dates of application for individual treatments are given in Table 1. The initial postbloom PCa spray was applied on 2 May when shoot growth averaged ≈ 2.75 inches. Subsequent postbloom PCa sprays were applied at 4 weeks or 6 weeks after the initial spray. In three of the treatments, a postbloom PCa spray schedule was combined with three or four low-dose (75 ppm) preharvest PCa sprays. Preharvest PCa sprays were initiated on 3 July or 18 July and GA₄₊₇ sprays were begun on 3 July (Table 1). Treatments were applied to whole trees in five randomized complete blocks. The number and length of water sprouts produced at the large pruning cuts on the central leader were recorded.

EXPT. 2. In 1998, sprays of PCa (BAS 125W 27.5DF) (27.5% a.i. dry flowable formulation) or GA₄₊₇ were applied to 7-year-old trees growing on several semidwarf rootstocks ['Malling.7' (M.7), M.9/MM.111, and MM.111]. All treatments were assigned equally across the rootstocks with single tree replicates in five randomized complete blocks. Regulaid was included in all sprays at 0.03% (v/v). The initial PCa spray was applied on 6 May when new shoot growth averaged 4 to 6 inches in length. The second PCa spray was applied 4 weeks later on 3 June. The rate of PCa for individual treatments is given in Table 2. GA₄₊₇ was applied beginning on 14 July.

Table 1. Effect of prohexadione–calcium (PCa) and gibberellin A4 plus A7 (GA₄₊₇) on shoot growth and fruit cracking in Stayman 201 apple (Expt. 1–1997).^z

Treatment				Terminal shoot length (cm) ^x	Length of water sprouts ^w (cm)	Cracked fruit (%)
PCa (ppm) ^y	Application date	GA ₄₊₇ (ppm)	Application date			
125, 125, 75	2 May, 30 May, 18 July	0	—			
75, 75, 75	1 Aug., 15 Aug., 29 Aug.			29.6 b ^v	40.4 bc	74.6 ab
250, 75, 75	2 May, 18 July, 1 Aug.	0	—			
75, 75	15 Aug., 29 Aug.			30.4 b	26.4 c	80.2 a
125, 250, 50	2 May, 11 June, 3 July	0	—			
50, 50	1 Aug., 29 Aug.			27.6 b	36.6 c	77.7 ab
125, 125, 125	2 May, 30 May, 11 June	37.5, 37.5, 25	3 July, 18 July, 1 Aug.			
		25, 25	15 Aug., 29 Aug.	32.6 b	61.8 ab	48.6 c
250, 125	2 May, 30 May	37.5, 25, 25	3 July, 18 July, 1 Aug.			
		25, 25	15 Aug., 29 Aug.	30.6 b	71.4 a	71.0 ab
0	—	37.5, 37.5, 25	3 July, 18 July, 1 Aug.			
		25, 25	15 Aug., 29 Aug.	49.2 a	72.0 a	21.6 d
0	—	0	—	46.6 a	76.6 a	63.8 b
			<i>P</i>	0.0007	0.0084	0.0001

^zSprays applied dilute with handgun sprayer to drip. PCa applied as BAS 125 10W (BASF Corp., Agricultural Products Group, Research Triangle Park, NC) and GA₄₊₇ applied as ProVide (Valent BioSciences Corp., Libertyville, IL). Regulaid (Kalo, Overland Park, KS) included at 0.03% (v/v).

^y1 ppm = 1 mg·L⁻¹.

^x1 cm = 0.3937 inch.

^wShoots produced on central leader at sites of large pruning cuts.

^vData analyzed using one-way analysis of variance. Mean separation within columns by Fisher's protected least significant difference at *P* ≤ 0.10.

Table 2. Effect of prohexadione–calcium (PCa) and gibberellin A4 plus A7 (GA₄₊₇) on fruit cracking in Stayman 201 apple trees on several rootstocks (Expt. 2–1998).^z

Treatment			Cracked fruit (%)
PCa ^y	GA ₄₊₇ ^x	(ppm) ^w	
0	0		18.5 ab ^v
0	37.5, 37.5, 25, 25, 25		7.4 b
125, 250	0		30.0 a
125, 250	37.5, 37.5, 25, 25, 25		16.5 ab
250, 125	37.5, 37.5, 25, 25, 25		12.0 b
63, 250	37.5, 37.5, 25, 25, 25		16.1 ab

Subset analysis for fruit cracking (%) with PCa (– or +) or GA₄₊₇ (– or +) as a contrast using all treatments above^u:

GA ₄₊₇	PCa			<i>P</i>
	–	+	Mean	
–	18.5	30.0	24.2 a	0.0502
+	7.4	16.5	12.0 b	
Mean	13.0 b	23.3 a		
<i>P</i>	0.0962			

^zSprays applied dilute with handgun sprayer to drip. PCa applied as BAS 125 27.5DF (BASF Corp., Agricultural Products Group, Research Triangle Park, NC) and GA₄₊₇ applied as ProVide (Valent BioSciences Corp., Libertyville, IL). Regulaid (Kalo, Overland Park, KS) included at 0.03% (v/v). PCa sprays included ammonium sulfate as a water conditioner on an equal weight basis with PCa.

^yInitial spray applied 6 May at 4 to 6 inches growth stage (1 inch = 2.54 cm); second spray applied 3 June.

^wFive sprays applied, one each on 14 July, 28 July, 16 Aug., 25 Aug., and 8 Sept. at concentration indicated.

^x1 ppm = 1 mg·L⁻¹.

^vOne-way analysis of variance; mean separation by Fisher's protected least significant difference at *P* ≤ 0.10.

^uTwo-way analysis of variance; interaction *P* = 0.8430.

EXPT. 3. A group of 8-year-old trees on MM.111 was selected for treatment in 1999. Treatments were arranged in a 2 × 4 factorial with PCa and GA₄₊₇ (Table 3). Four rates of

PCa [0, 3, 6, and 12 oz/100 gal TRV formulated product (Apogee 27.5DF)] were selected for application at three postbloom timings [petal fall (PF) + 7 d, PF + 28 d, and PF + 42 d] with or

without preharvest GA₄₊₇ sprays (Table 3). The calculated TRV for the test plot was 330 gal/acre and the calculated PCa dose was applied in a carrier volume of 164 gal/acre. Regulaid was included at 0.03% (v/v) in all PCa sprays. Bio-88, a nonionic spreader-activator (blend of alkylaryl-polyethoxyethanol, free fatty acids, 2-butylether, and dimethylpolysiloxane; Kalo) was included in all GA₄₊₇ sprays at 0.03% (v/v).

EXPT. 4. Treatments of PCa and GA₄₊₇ were arranged as a 2 × 2 factorial (Table 4) and applied to mature bearing trees on M.7 rootstock in a commercial orchard near Kearneysville, WV, in 2000. Forty uniform trees with moderate to heavy cropping potential, based on bloom density, were selected and assigned to four treatments with 10 single-tree replications in a randomized complete block design. PCa was applied in two sprays, the first on 3 May when shoot growth averaged 3 inches and the second spray 3 weeks later on 24 May. The initial PCa spray was applied at a rate based on 12 oz/100 gal TRV formulated product (Apogee 27.5DF) and the second spray was applied at a rate based on 6 oz/100 gal TRV. The calculated TRV for the test orchard was 290 gal/acre. Spray treatments were applied in a carrier volume of 100 gal/acre. Regulaid was included in all

Table 3. Effect of prohexadione-calcium (PCa) and gibberellin A4 plus A7 (GA₄₊₇) on shoot growth and fruit cracking in Stayman 201 apple trees (Expt. 3-1999).^z

			Treatment					Terminal shoot length (cm) ^y	Cracked fruit (%)
PCa (oz/100 gal TRV) applied ^y			GA ₄₊₇ (ppm) ^x applied						
PF + 7 ^w	PF + 28	PF + 42	1 July	15 July	29 July	12 Aug.	26 Aug.		
0	0	0	0	0	0	0	0	39.6	48.0
0	0	0	37.5	37.5	25	25	25	33.6	19.4
6	3	0	0	0	0	0	0	23.8	58.2
6	3	0	37.5	37.5	25	25	25	24.7	29.5
6	6	6	0	0	0	0	0	18.5	53.5
6	6	6	37.5	37.5	25	25	25	27.7	27.6
12	6	0	0	0	0	0	0	22.4	69.2
12	6	0	37.5	37.5	25	25	25	31.4	44.6

Two-way analysis of variance for terminal shoot length (cm) with PCa (four treatment levels) and GA₄₊₇ (– or +)^u:

GA ₄₊₇	PCa					P
	0-0-0	6-3-0	6-6-6	12-6-0	Mean	
–	39.6	23.8	18.5	22.4	26.6 a	0.3623
+	33.6	24.7	27.7	31.4	29.5 a	
Mean	36.6 a	24.3 b	23.1 b	26.0 b		
P	0.0005					

Two-way analysis of variance for fruit cracking (%) with PCa (four treatment levels) and GA₄₊₇ (– or +)[†]:

GA ₄₊₇	PCa					P
	0-0-0	6-3-0	6-6-6	12-6-0	Mean	
–	48.0	58.2	53.5	69.2	57.3 a	0.0001
+	19.4	29.5	27.6	44.6	29.0 b	
Mean	33.7 c	42.2 b	40.6 bc	59.3 a		
P	0.0017					

^zSprays applied dilute with handgun sprayer to drip. PCa applied as Apogee 27.5DF (BASF Corp., Agricultural Products Group, Research Triangle Park, NC). GA₄₊₇ applied as ProVide (Valent BioSciences Corp., Libertyville, IL). PCa sprays included ammonium sulfate as a water conditioner on an equal weight basis with PCa and Regulaid (Kalo, Overland Park, KS) at 0.03% (v/v); GA₄₊₇ sprays included the adjuvant Bio-88 (Kalo) at 0.03% (v/v).

^yRate in oz/100 gal (1 oz/100 gal = 0.0749 g·L⁻¹) of Apogee 27.5DF applied at dose based on a tree-row-volume (TRV) calculated as 330 gal/acre in a spray solution of 164 gal/acre (1 gal/acre = 9.3540 L·ha⁻¹).

^x1 ppm = 1 mg·L⁻¹.

^wPetal fall (PF) on 4 May. PF + 7 = petal fall + 7 d; PF + 28 = petal fall + 28 d; and PF + 42 = petal fall + 42 d.

^v1 cm = 0.3937 inch.

^uMean separation by Fisher's protected least significant difference (LSD) at $P \leq 0.10$; interaction $P = 0.0741$.

[†]Mean separation by Fisher's protected LSD at $P \leq 0.10$; interaction $P = 0.9617$.

sprays at 0.125% (v/v) and the final spray solution was adjusted to pH 6.0 with distilled white vinegar.

EXPT. 5. In 2000, a study was conducted to examine the effect of several spray adjuvants in combination with PCa on the incidence of 'Stayman' cracking. Seven treatments were assigned at random to single 9-year-old trees on MM.111 rootstock in seven replicated plots. Five adjuvants were evaluated in combination with PCa: Regulaid, Bio-88, Silwet L77 (polyalkyleneoxide-modified heptamethyltrisiloxane; Helena Chemical Co., Collierville, TN), DyneAmic (a proprietary blend of polyalkyleneoxide modified polydimethyltrisiloxane, nonionic emulsifiers, and methylated vegetable oils; Helena Chemical Co.), and Damoil

(70-s delayed dormant spray oil; Drexel Chemical Co., Memphis, TN). Adjuvants were used at the manufacturer's suggested concentration (Table 5). PCa was applied in two sprays at 6 oz/100 gal TRV (as Apogee 27.5DF) per spray. The initial spray was applied on 27 Apr. when terminal shoot growth averaged 6.6 cm in length. The second spray was applied on 12 May. The calculated TRV for test plot trees was 400 gal/acre and sprays were applied in a carrier volume of 100 gal/acre. The final spray solution was adjusted to pH 6.5 with distilled white vinegar.

EXPT. 6. Spray treatments applied in Expt. 4 were repeated in 2001 on a group of 10-year-old trees on MM.111 rootstock growing at the AFRS location (Table 6). Four

treatments were assigned to 11 single-tree replications in a randomized complete-block design. The initial PCa spray was applied on 8 May when terminal growth averaged 7.3 cm in length. The second PCa spray was applied on 24 May. The calculated TRV for the test trees was 390 gal/acre and all sprays were applied in a carrier volume of 270 gal/acre.

Results

EXPT. 1. Mean yield per tree and fruit weight did not differ among treatments (data not shown). All treatments that included PCa reduced the length of terminal shoots (Table 1). Five preharvest GA₄₊₇ sprays alone had no effect on terminal shoot length or the length of water sprouts. When PCa was applied in

Table 4. Shoot growth and fruit cracking in Stayman 201 apple trees treated with prohexadione-calcium (PCa) or gibberellin A4 plus A7 (GA₄₊₇) (Expt. 4–2000).^z

Two-way analysis of variance for terminal shoot length (cm) with PCa (– or +) and GA ₄₊₇ (– or +) ^y :				
GA ₄₊₇	PCa		Mean	P
	–	+		
–	24.2	10.7	17.5 a	0.9913
+	24.2	10.8	17.5 a	
Mean	24.2 b	10.8 a		
P	0.0028			
Two-way analysis of variance for fruit cracking (%) with PCa (– or +) and GA ₄₊₇ (– or +) ^x :				
GA ₄₊₇	PCa		Mean	P
	–	+		
–	34.1	54.4	44.2 a	0.1650
+	25.5	40.4	32.9 a	
Mean	29.8 b	47.4 a		
P	0.0346			

^zSprays applied dilute with handgun sprayer to drip. PCa applied as Apogee 27.5DF (BASF Corp., Agricultural Products Group, Research Triangle Park, NC) in two sprays at 100 gal/acre based on a tree-row-volume (TRV) of 290 gal/acre; initial spray applied on 3 May at 12 oz/100 gal (0.90 g·L⁻¹) TRV and second spray applied 24 May at 6 oz/100 gal TRV. PCa sprays included ammonium sulfate as a water conditioner on an equal weight basis with PCa and Regulaid (Kalo, Overland Park, KS) at 0.125% (v/v). Final spray solution adjusted to pH 6.0 with distilled white vinegar. GA₄₊₇ applied as ProVide (Valent BioSciences Corp., Libertyville, IL) in five sprays at 2-week intervals with initial spray applied on 30 June. First two sprays applied at concentration of 37.5 ppm and last three sprays applied at 25 ppm. Regulaid included in all sprays at 0.125% (v/v) (1 gal/acre = 9.3540 L·ha⁻¹, 1 oz/100 gal = 0.0749 g·L⁻¹, 1 ppm = 1 mg·L⁻¹).

^yMean separation by Fisher's protected least significant difference (LSD) at $P \leq 0.10$. Interaction $P = 0.9913$.

^xMean separation by Fishers protected LSD at $P \leq 0.10$. Interaction $P = 0.7417$.

Table 5. Effect of prohexadione-calcium (PCa) alone or combined with several spray adjuvants on terminal shoot length and fruit cracking in Stayman 201 apple trees (Expt. 5–2000).

Adjuvant ^y	Treatment ^z		Terminal shoot length (cm)	Cracked fruit (%)
	Concn (% v/v)	PCa (– or +)		
None	0	–	26.4 a ^x	25.7 c
None	0	+	17.5 b	36.9 bc
Silwet L77	0.062	+	17.5 b	52.6 ab
Regulaid	0.125	+	19.0 b	49.3 b
Bio-88	0.125	+	18.3 b	49.5 b
Damoil	0.250	+	18.7 b	45.4 b
DyneAmic	0.380	+	18.9 b	71.6 a
		P	0.0001	0.0124

^zSprays applied with handgun sprayer to wet fruit and foliage (drip). PCa applied as Apogee 27.5DF (BASF Corp., Agricultural Products Group, Research Triangle Park, NC) in two sprays at 6 oz/100 gal tree-row-volume (TRV) each based on a calculated TRV of 400 gal/acre in a carrier spray volume of 100 gal/acre; initial spray applied on 27 Apr. and second spray applied 12 May. PCa sprays included ammonium sulfate as a water conditioner on an equal weight basis with PCa. Spray solution adjusted to pH 6.5 with distilled white vinegar (1 oz/100 gal = 0.0749 g·L⁻¹, 1 gal/acre = 9.3540 L·ha⁻¹).

^ySilwet L77 and DyneAmic, Helena Chemical Co., Collierville, TN; Regulaid and Bio-88, Kalo, Overland Park, KS; and Damoil (70-s delayed dormant spray oil), Drexel Chemical Co., Memphis, TN.

^xMean separation within columns by Fisher's protected least significant difference at $P \leq 0.10$.

two or three postbloom sprays followed by preharvest GA₄₊₇ sprays, terminal growth was reduced similar to that on trees treated with postbloom plus preharvest PCa alone. Water sprout growth was reduced on trees treated with postbloom plus preharvest PCa. The length of water sprouts was unaffected when PCa was

applied postbloom only followed by GA₄₊₇ preharvest sprays. Five preharvest sprays of GA₄₊₇ alone reduced fruit cracking from 64% (considered severe) to 22% (moderately low). A single postbloom PCa spray at 250 ppm followed by four preharvest PCa sprays at 75 ppm each increased the level of fruit cracking. The level of

fruit cracking was unaffected when two postbloom PCa sprays were applied, the initial spray at 125 ppm, followed by three or four preharvest PCa sprays (Table 1). Three postbloom PCa sprays at 125 ppm each followed by the preharvest GA₄₊₇ treatment reduced fruit cracking compared with controls, but the level of cracking was still greater than that obtained with the GA₄₊₇ treatment alone. When two postbloom PCa sprays were applied, the initial spray at 250 ppm, followed by preharvest GA₄₊₇, the percentage of fruit cracking did not differ from the controls.

Expt. 2. Preharvest GA₄₊₇ sprays reduced the percent of cracked fruit by 60% compared with the control (Table 2). Trees treated with PCa alone had significantly more cracked fruit than trees treated with GA₄₊₇ alone. Applying GA₄₊₇ as a preharvest treatment to trees that received postbloom PCa sprays reduced cracking by 45% to 60% compared with trees treated with PCa alone. A two-way ANOVA of the data set with contrast statements showed that PCa increased cracking, whereas GA₄₊₇ treatment reduced fruit cracking. The two-way interaction of PCa × GA₄₊₇ was nonsignificant ($P = 0.8430$).

Expt. 3. A two-way analysis of the main treatment effects showed no significant effect of GA₄₊₇ on terminal shoot length, but a significant reduction in terminal length with PCa at all treatment levels (Table 3). The interaction between PCa and GA₄₊₇ for terminal shoot length was significant ($P = 0.0741$).

Across all treatments, spraying 'Stayman 201' apple trees with GA₄₊₇ reduced fruit cracking in 1999 (Table 3). GA₄₊₇ alone reduced the percentage of cracked fruit from 48% to 19%, a 60% reduction in fruit cracking. PCa generally increased fruit cracking. Trees treated with PCa at 12 oz/100 gal TRV at the PF + 7 d timing followed by a second spray at PF + 28 d at 6 oz/100 gal TRV exhibited the highest percentage of cracked fruit. Trees treated at the lowest total PCa dose rate (6 oz/100 gal at PF + 7 d followed by 3 oz/100 gal at PF + 28 d) also showed an increase in the percentage of cracked fruit compared with the non-PCa-treated control trees. When PCa was applied in three equal rate sprays (6

Table 6. Shoot growth and fruit cracking in Stayman 201 apple trees treated with prohexadione-calcium (PCa) or gibberellin A4 plus A7 (GA₄₊₇) (Expt. 6–2001).^z

Two-way analysis of variance for terminal shoot length (cm) with PCa (– or +) and GA ₄₊₇ (– or +) ^y :				
GA ₄₊₇	PCa		Mean	P
	–	+		
–	46.2	20.5	33.3 b	0.0531
+	49.8	26.8	38.3 a	
Mean	48.0 b	23.6 a		
P	0.0001			

Two-way analysis of variance for fruit cracking (%) with PCa (– or +) and GA ₄₊₇ (– or +) ^y :				
GA ₄₊₇	PCa		Mean	P
	–	+		
–	11.7	24.9	18.3 a	0.0001
+	6.1	9.4	7.7 b	
Mean	8.9 b	17.2 a		
P	0.0001			

^zSprays applied dilute with handgun sprayer to drip. PCa applied as Apogee 27.5DF (BASF Corp., Agricultural Products Group, Research Triangle Park, NC) in two sprays at 270 gal/acre based on a tree-row-volume (TRV) of 390 gal/acre; initial spray applied on 8 May at 12 oz/100 gal TRV and second spray applied 24 May at 6 oz/100 gal TRV. PCa sprays included ammonium sulfate as a water conditioner on an equal weight basis with PCa and Regulaid (Kalo, Overland Park, KS) at 0.125% (v/v). Final spray solution adjusted to pH 6.0 with distilled white vinegar. GA₄₊₇ applied as ProVide (Valent BioSciences Corp., Libertyville, IL) in five sprays at 2-week intervals with initial spray applied on 1 July. First two sprays applied at concentration of 37.5 ppm and last three sprays applied at 25 ppm. Regulaid included in all sprays at 0.125% (v/v) (1 gal/acre = 9.3540 L·ha⁻¹, 1 oz/100 gal = 0.0749 g·L⁻¹, 1 ppm = 1 mg·L⁻¹).

^yMean separation by Fisher's protected least significant difference (LSD) at $P \leq 0.10$. Interaction $P = 0.5961$.

^xMean separation by Fisher's protected LSD at $P \leq 0.10$. Interaction $P = 0.0139$.

oz/100 gal), the percentage of cracked fruit did not differ from control trees. At each PCa treatment level, the percentage of cracked fruit at harvest was reduced when GA₄₊₇ was applied, but the percent reduction was less than that obtained in the non-PCa-treated trees. The PCa and GA₄₊₇ interaction was not significant ($P = 0.9617$).

EXPT. 4. Mean yield per tree and fruit weight did not differ among treatments (data not shown). Two sprays of PCa reduced terminal shoot length an average of 56% (Table 4). GA₄₊₇ sprays applied preharvest alone or to trees previously treated with PCa had no effect on terminal shoot length. The interaction of PCa and GA₄₊₇ for terminal shoot length was not significant ($P = 0.9913$). Based on the two-way analysis of fruit cracking data, PCa treatment increased fruit cracking, but GA₄₊₇ treatment failed to reduce cracking, although the percentage of cracked fruit declined slightly from $\approx 44\%$ to $\approx 33\%$ (Table 4).

EXPT. 5. Two postbloom sprays of PCa alone or combined with one of five different spray adjuvants reduced

terminal shoot length of 'Stayman 201' trees (Table 5). There were no differences in terminal shoot length among the five adjuvants tested. The percentage of cracked fruit was increased on all trees sprayed with PCa plus an adjuvant, but not on the trees treated with PCa minus an adjuvant. The highest percentage of cracked fruit occurred with PCa plus Silwet L77 or DyneAmic, both organosilicone adjuvants (Table 5). In general, the addition of a spray adjuvant to the PCa spray treatment increased the percentage of cracked fruit by 45% on the 'Stayman' apples in the test plot. Spraying with PCa alone increased the percentage of cracked fruit by 44%.

EXPT. 6. Mean yield per tree and fruit weight did not differ among treatments (data not shown). Two sprays of PCa applied in May reduced terminal shoot length (Table 6). Five GA₄₊₇ sprays at 2-week intervals beginning 1 July increased terminal shoot length, but only an average of 5 cm. The interaction of PCa and GA₄₊₇ for terminal shoot length was not significant ($P = 0.5961$). GA₄₊₇

treatment significantly reduced the percentage of cracked fruit, whereas PCa treatment increased the percentage of cracked fruit, an increase of $\approx 93\%$ (Table 6). A significant interaction ($P = 0.0139$) existed between PCa and GA₄₊₇ treatment for fruit cracking. GA₄₊₇ was more efficient in reducing the percentage of cracked fruit in PCa-treated trees than in trees that had not been treated with PCa.

Discussion

In the present study, PCa was generally applied in multiple sprays at rates of 125 ppm (6 oz/100 gal) or 250 ppm (12 oz/100 gal) or combinations of these rates. In several experiments (Expt. 1, 2, and 3), lower dose [50 ppm, 63 ppm (3 oz/100 gal), or 75 ppm] treatments were applied, but these were the exception. The higher rates and multiple spray applications used in these experiments conform to label recommendations for growth control in moderate to vigorous trees (BASF Corp., 2001) and published reports on the use of PCa in the mid-Atlantic region (Byers and Yoder, 1999; Byers et al., 2004a; Miller, 2002).

Yield and fruit weight were unaffected by the application of PCa in this study. Some previous studies have reported increases in fruit set and yield after PCa sprays (Byers et al., 2004a; Glenn and Miller, 2005; Greene, 1999; Medjdoub et al., 2005; Schupp et al., 2003), whereas other studies found no effect on fruit set and yield (Byers and Yoder, 1999; Miller, 2002; Medjdoub et al., 2005; Schupp et al., 2003). Reports on the effect of PCa on fruit size have also varied with some showing reduced fruit size after PCa treatment (Glenn and Miller, 2005; Greene, 1999; Medjdoub et al., 2005; Schupp et al., 2003), but other studies have found no effect (Byers and Yoder, 1999; Miller, 2002; Schupp et al., 2003). It is unclear how PCa may lead to increased fruit set, but Rademacher et al. (1998) suggest it may be related to the ability of PCa to block the conversion of 1-amino-cyclopropane-1-carboxylic acid to ethylene, the abscission hormone. Greene (1999) attributed reduced fruit size after PCa to an increase in fruit set. Studies by Glenn and Miller (2005)

indicated that a reduction in fruit size after PCa application was related to increased fruit numbers and not a direct response to the PCa. It would appear that additional studies examining the effect of PCa on fruit set and fruit size are warranted.

Results from this study agree with earlier reports that demonstrated the growth controlling properties of PCa (Byers and Yoder, 1999; Byers et al., 2004b; Greene, 1999; Miller, 2002; Rademacher et al., 2004; Schupp et al., 2001). In five separate experiments over a period of 4 years, PCa consistently reduced terminal shoot length in 'Stayman 201' apple trees compared with the controls. No conclusions can be drawn from Expt. 1 concerning the effect of preharvest PCa sprays on terminal shoot growth because no preharvest PCa-only treatment was included in the study.

A combination of postbloom and preharvest PCa sprays (Expt. 1) reduced the growth of water sprouts produced near pruning cuts. Growth of water sprouts was unaffected when PCa was applied as postbloom sprays only followed by preharvest GA₄₊₇ spray treatment. Schupp et al. (2003) reported that two PCa sprays applied soon after bloom in May had no effect on the growth of water sprouts produced on 'Empire' apple trees growing in New York or New Jersey. They concluded that PCa was applied too early to reduce the growth of water sprouts that are initiated after the first flush of terminal growth. The results in Expt. 1 illustrate the ability of PCa to control water sprout growth when applied in a combination of early (postbloom) plus late (preharvest) spray treatments. Unfortunately, this study did not include a postbloom-only or a preharvest-only PCa treatment, which may have provided some clarification as to the optimum timing of PCa for control of water sprout growth.

Regulaid was used as an adjuvant with PCa sprays in all experiments. When four other adjuvants, applied at the manufacturer's recommended rates, were compared with Regulaid (Expt. 5), there was no difference in the level of shoot growth control obtained among the adjuvants tested (Table 5). Byers et al. (2004b) reported that oil + Silwet L77 combined with PCa provided better shoot

growth suppression on 'Fuji' apple trees than Regulaid, although the differences were small. In their study, three applications of PCa (as Apogee 27.5DF) at 125 ppm without an adjuvant reduced shoot growth compared with controls, but the level of growth reduction was enhanced when Regulaid or oil + Silwet L77 was added to the spray mixture. In the present study, the addition of any one of five different adjuvants did not increase growth suppression in 'Stayman 201' trees compared with trees sprayed with two PCa sprays alone. Other factors such as hard water can influence the growth response to PCa (Byers et al., 2004b; Schupp et al., 2003). In the present study, sprays were prepared using high calcium content well water; however, a water conditioner (AMS) was used in all sprays except those in Expt. 1. Both the 10% and 27.5% formulations of PCa contain AMS, but the 10% material, which was used in Expt. 1, has a higher AMS content (90% AMS) than the 27.5% formulation (56.1% AMS) used in the remaining experiments. The results for growth control in Expt. 5 suggest that the choice of adjuvant is not as important as long as PCa sprays are applied to achieve good coverage and under conditions that support maximum absorption (slow drying and high relative humidity).

Gibberellins increase shoot growth through their effect on cell elongation (Métraux, 1987). Guak et al. (2001) reversed the growth-retarding effect of PCa on apple when they applied GA₄₊₇ 1 d after PCa treatment. Miller et al. (2002) reported that GA₄₊₇ applied to apple trees in four sprays (PF + 10 d, + 20 d, + 30 d, and + 40 d) at 15 ppm reduced the level of growth control obtained from two PCa sprays. Byers et al. (2004a) applied GA₃ at 213 ppm as a tank mix with PCa in three sprays (PF, PF + 21 d, and PF + 53 d) and reduced the growth suppression obtained with PCa alone. Miller et al. (2002) and Byers et al. (2004a) found no growth promotion from GA sprays alone, but Guak et al. (2001) reported growth of GA₄₊₇-treated trees was greater than that of control trees. In studies previously mentioned, the GA material was applied at or near the time of the PCa application and just before the period of rapid growth in apple. In

the present study, GA₄₊₇ applied preharvest did not promote terminal shoot growth in any of the individual experiments except Expt. 6 (Table 6). In Expt. 3, the preharvest GA₄₊₇ sprays partially reversed the growth suppression obtained with PCa applied postbloom as indicated by the significant interaction ($P = 0.0741$) between PCa and GA₄₊₇. GA₄₊₇ alone did not affect the growth of water sprouts (Expt. 1). The lack of a postbloom PCa-only treatment in Expt. 1 prevents concluding that GA sprays interfered with the growth-suppressing activity of postbloom PCa treatment (Table 1).

Cracking of 'Stayman' apples varies from year to year, between sites, and sometimes even between trees on a given site (Byers and Carbaugh, 1995; Opara et al., 1997; Stiles et al., 1959; Verner, 1935). In this study, cracking varied from a low of 11.7% in 2001 to a high of 63.8% in the 1997 experiment. GA₄₊₇, applied preharvest, beginning approximately 1 July in five biweekly sprays, reduced cracking in 'Stayman 201' apples an average of 52% compared with fruit on control trees in experiments from 1997 through 2001. Previous studies, which have demonstrated the effectiveness of GA₄₊₇ for reducing 'Stayman' fruit cracking, have also shown that the level of control can vary (Byers et al., 1990; Unrath, 1991). In this study, there appeared to be no correlation between the level of cracking control achieved with GA₄₊₇ and the natural level of cracking.

Postbloom applications of PCa increased in the percentage of cracked fruit in four experiments (Expts. 2, 3, 4, and 6). In Expt. 5, postbloom PCa increased cracking compared with untreated controls when an adjuvant was included with the PCa sprays. An adjuvant was included in all other experiments when PCa was applied. In Expt. 1, the percentage of cracked fruit was increased with a high-dose (250 ppm) postbloom PCa spray combined with multiple low-dose (75 ppm) preharvest PCa sprays. Although the results of this study might suggest that the multiple postbloom high-dose [250 ppm (12 oz/100 gal) followed by 125 ppm (6 oz/100 gal)] treatments (Expts. 1, 3, 4, and 6) were responsible for increased fruit cracking, cracking was also

increased with multiple low-dose [125 ppm (6 oz/100 gal) followed by 63 ppm (3 oz/100 gal)] post-bloom sprays (Expt. 3). In the only published report involving PCa application on 'Stayman' apple trees, Byers and Yoder (1999) found no effect of a single application of PCa at 125, 250, or 375 ppm on 'Stayman' cracking. PCa as a single-spray treatment was not applied in any of the experiments in this study because the author has observed over several years that single sprays result in unacceptable growth control in most apple cultivars growing under mid-Atlantic conditions compared with multiple sprays. Schupp et al. (2003) reported severe fruit cracking on 'Empire' apple treated with PCa in two of three trials in New York and New Jersey. They concluded that the injury was incited by PCa under certain environmental conditions. Fruit cracking in this study varied with year and specific treatment, but the majority of the evidence supports the hypothesis that PCa increases cracking in the 'Stayman' apple similar to its effect on Empire cracking as reported by Schupp et al. (2003).

When 'Stayman' apples were treated postbloom with PCa followed by preharvest sprays of GA₄₊₇, the level of cracking was generally reduced, but not always (e.g., Expt. 4). Despite the ability of GA₄₊₇ to reduce the level of fruit cracking in PCa-treated trees, the reduction was not always to the same extent as that achieved by GA₄₊₇ in non-PCa-treated trees. An example is Expt. 3 in which GA₄₊₇ alone reduced fruit cracking from 48% to 19.4%, a 60% reduction in the level of cracking. However, when trees were treated with a 12-oz/100 gal spray followed by a 6-oz/100 gal spray of PCa, the preharvest GA₄₊₇ treatment reduced cracking from 69.2% to 44.6%, a reduction of only 36% in the level of cracking. A 44% level of cracking would be commercially unacceptable.

Byers et al. (1990) found that submerging 'Stayman' apples in a nonionic surfactant (adjuvant) solution increased cracking compared with a water-only submersion. They did not evaluate the effect of surfactant sprays alone on cracking in the field. In a later study, Byers et al. (2004b) increased cracking in 'Empire' apples compared with a

control with three sprays of PCa (27.5% formulation) applied with AMS + Regulaid. A similar treatment with technical-grade PCa (93.2% material) had no effect on cracking in 'Empire' apples. They attributed the increase in cracking to increased absorption of PCa. Schupp et al. (2003) exacerbated the cracking and corking damage they found on 'Empire' apples treated with PCa when they added AMS to the spray. When they applied AMS + Regulaid without PCa, they found little or no effect on the level or severity of fruit injury in 'Empire'. In the current study, two PCa (27.5% formulation) sprays with AMS but without an adjuvant had no effect on fruit cracking ($P \leq 0.10$). The addition any one of five different adjuvants increased the percentage of cracked fruit above the untreated controls with the greatest increase associated with Silwet L77 or DyneAmic, both organosilicone surfactants. These results suggest that AMS plus an adjuvant may increase absorption of PCa and the potential for fruit cracking in a cultivar prone to cracking such as 'Stayman'.

Results of this study clearly demonstrate the ability of PCa to suppress shoot growth in 'Stayman' apple trees. Two applications of PCa between PF and ≈ 4 to 6 weeks after PF (postbloom period) were generally sufficient to reduce terminal shoot growth. Multiple preharvest applications of GA₄₊₇ generally had no effect on shoot growth, but in some instances partially reversed the shoot growth-suppressing effect of PCa. GA₄₊₇ spray treatments applied during the preharvest period generally reduced the incidence of fruit cracking; in PCa-treated and non-PCa-treated trees, however, the efficacy of GA₄₊₇ to reduce cracking was clearly affected by postbloom PCa. Results from six experiments over 5 years demonstrated that PCa applied postbloom in 'Stayman 201' apples can increase the incidence of fruit cracking in this cultivar. Adjuvants, especially the organosilicone-based materials, may enhance uptake of PCa and lead to an increase in the level of cracking. Based on the results of these experiments, the use of PCa to control shoot growth on 'Stayman' apple trees should be approached with a great deal of caution because of the likelihood that fruit cracking

will be increased, which may or may not be reversed by GA₄₊₇.

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