The Effect of Prohexadione-calcium on Fruit Set and Chemical Thinning of Apple Trees

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Abstract. Prohexadione-calcium (ProCa) has emerged as one of the most important management tools that an orchardist has available to control vegetative growth and to reduce the incidence and severity of fire blight. It has also been implicated in increased fruit set on treated apple trees. This investigation was initiated to confirm the effects of ProCa on fruit set and to evaluate different thinning strategies that might be used to appropriately thin treated trees. ProCa increased fruit set when applied at petal fall at initial rates of 125 or 250 mg·L⁻¹ in three of the four experiments described in this article. Thinners were applied before, at the time of, and after application of ProCa. In all experiments, chemical thinners did not reduce fruit set to the same crop load level on ProCa-treated trees as they did on untreated trees. It was concluded that a different and more aggressive chemical thinning strategy must be used on trees that were treated with ProCa. Fruit size was reduced on ProCa-treated trees. This reduction was usually, but not always, related to increased fruit set. ProCa increased the number of pygmy fruit on 'Delicious' apple trees.

Vegetative growth control in apples is one of the most basic and necessary activities that an orchardist is required to do. Frequently, vegetative growth is excessive and if not appropriately controlled, it could influence many aspects of fruit production, including flower bud formation, fruit set, fruit quality, physiological disorders, pest management, and postharvest fruit life.

Various methods of growth control have been practiced in the past (Greene, 2003; Miller, 1988). The widespread use of dwarfing rootstocks has been a major help in regulating vegetative growth. However, rootstock is only a partial solution to control vigorous vegetative growth because aberrant weather, frost, biennial bearing tendencies, lack of crop resulting from excessive thinning, and planting errors cause situations in which additional forms of growth control are needed.

Daminozide was used successfully for many years to control growth, but its registration was withdrawn for use on apples in 1989. Ethephon is an ethylene-liberating growth retardant that is currently available, but it may have limited use on bearing apple trees because the rate required for effective growth control can also lead to substantial thinning (Greene, 2003).

Prohexadione-calcium (ProCa) is a relatively new growth retardant that was labeled for use on apples in the United States in 1999. A number of reports have confirmed that it is

an effective growth retardant (Basak, 2004; Byers et al., 2004; Greene, 1999; Medjdoub et al., 2005; Miller, 2002; Rademacher and Kober, 2003; Unrath, 1999). To achieve maximum growth control, it must be applied as soon as sufficient foliage has emerged to allow for foliar penetration (Byers and Yoder, 1999; Miller, 2002; Rademacher and Kober, 2003; Unrath, 1999). Generally, the timing of the first application is at petal fall (PF) (Rademacher and Kober, 2003). ProCa is rapidly inactivated within the tree (Rademacher et al., 2004). There is general agreement among those reporting satisfactory growth control that one or more follow-up applications of ProCa are necessary to achieve season-long growth control, especially when lower rates are used (Miller, 2002).

During the development and testing of ProCa, it was discovered that it was effective at reducing the shoot blight phase of fire blight (Yoder et al., 1999). Effective control generally required application at the highest rate of ProCa recommended on the label. The time of initial application for fire blight control was at PF, similar to that for vegetative growth control. A reduction in shoot growth appears to be a prerequisite for effective fire blight control with ProCa (Norelli and Miller, 2004). Closely associated with this growth reduction is a buildup of pathogen resistance, which is attributed to a novel flavonoid, leuteoferol (Rademacher, 2004).

Usually there are both positive and negative effects where a plant growth regulator is applied to regulate a physiological response on a crop. Adjustments are most often made

in concentration applied, the time of application, or use that often minimize the undesirable effects while preserving the positive effects (Greene, 2002a). ProCa is no exception. Although the greatest degree of growth control is frequently observed when high rates are used (Medjdoub et al., 2005; Miller, 2002), these rates may result in increased fruit set and result in fruit that appear to be less susceptible to normal thinner application (Miller, 2002). Because effective and appropriate crop load management is a key to profitable apple production, it will be important to develop strategies for using ProCa that minimize increased fruit set and allow for effective and predictable chemical thinner action.

The purpose of this investigation was to confirm the effect of ProCa on fruit set and to examine several chemical thinning strategies that may be used to effectively and appropriately thin ProCa-treated apple trees.

Materials and Methods

Expt. 1, prohexadione-calcium concentration, 'McIntosh'. A block of mature 'McIntosh'/M.7 apples was selected growing at the Horticultural Research Center, Belchertown, MA. Twenty-four trees were selected and before bloom, two limbs per tree 10 to 15 cm in circumference were selected, tagged, measured, and then all blossom clusters counted. Blossom cluster density was calculated and then trees were blocked into six groups (replications) of four trees each based on blossom density. Two trees in each block were sprayed with 125 mg·L⁻¹ ProCa containing 0.05% v/v Regulaid (Kalo, Overland Park, KS) at PF on 31 May when shoot length averaged ≈8 cm. A third tree in each block was sprayed on the same day with 250 mg·L⁻¹ ProCa with Regulaid. On 28 June, one tree in each block that previously received 125 mg·L⁻¹ ProCa was again sprayed with 125 mg·L⁻¹ ProCa. All spray treatments were made as a dilute hand gun application to drip. One tree in each block was not treated and served as the control. All trees in the block received a normal postbloom thinning regime, which included a petal fall application of carbaryl at a rate of 1000 mg·L⁻¹ followed by another thinning spray 10 d later containing 5 mg·L⁻¹ naphthaleneacetic acid (NAA) and 1000 mg·L⁻¹ of carbaryl. At the end of June drop, all fruit on tagged limbs were counted and fruit set calculated based on bloom or limb cross-sectional area. At the normal harvest time in September, 30 fruit per tree were harvested and weighed. After leaf fall in November, the terminal growth of 20 randomly selected shoots per tree was taken.

Expt. 2, naphthaleneacetic acid timing, 'McIntosh'. A block of mature 'McIntosh'/M.106 apples was selected in a commercial orchard located in Belchertown, MA. Fifty-six trees were selected and before bloom, two limbs per tree 10 to 15 cm in circumference were selected, tagged, measured, and then all

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blossom clusters were counted. Blossom cluster density was calculated and then trees were blocked into seven groups (replications) of eight trees each based on blossom density and proximity in the orchard. ProCa at 250 mg·L⁻¹ in 0.05% v/v Regulaid was applied to four trees in each group as a dilute hand gun application on 31 May, when terminal growth averaged 11.7 cm. At PF, which occurred on 23 May, NAA at 10 mg·L⁻¹ was applied to two trees in each replication, one that would subsequently receive ProCa and one that would receive only the NAA thinning treatment. NAA at 10 mg·L⁻¹ was applied on 31 May when fruit size averaged 8.7 mm to one tree that previously received ProCa and one that did not. Likewise, on 6 June, when fruit size averaged 13.8 mm, 10 mg·L⁻¹ NAA was applied to one untreated tree and one tree that received ProCa in each replication. The total number of fruit on each tagged limb was counted at the end of June drop in July and fruit set calculated. At the normal time of harvest on 6 Sept., 30 fruit were harvested randomly from the periphery of each tree, weighed, and means calculated.

Expt. 3, thinning combinations, 'Delicious'. In a block of mature 'Ace Delicious'/M.26 located at the Horticultural Research Center, Belchertown, 64 trees were selected. Limbs were tagged, blossom clusters counted before bloom, and trees were blocked into eight groups (replications) containing eight trees each in a manner similar to that described in Expt. 1. On 26 May, 2 d after PF, a spray containing 10 mg·L⁻¹ NAA and 600 mg·L⁻¹ carbaryl was applied with an airblast sprayer to two trees in each block. The remaining thinner treatments were applied on 2 June when fruit size averaged 9.6 mm. NAA at 8 mg·L⁻¹ was applied to two trees in each block, whereas another two trees in each replication received 8 mg·L⁻¹ NAA plus 600 mg·L⁻¹ carbaryl. ProCa at 250 mg·L⁻¹ containing 0.03% v/v Regulaid was also applied on 2 June when terminal growth averaged 9.0 cm. All spray treatments were applied with a commercial airblast sprayer at a tree-row-volume (TRV) of 1168 L·ha⁻¹. Fruit set was assessed at the end of June drop and 30 fruit per tree were harvested from each tree at the normal harvest time as previously described. The pygmy fruit present in each fruit sample were counted. Pygmy fruit were not included when weighing fruit to determine the effects of treatments on fruit weight. Return bloom was determined by selecting two limbs per tree 10 to 15 cm in diameter and then counting all blossom clusters on the tagged portion of the limb at the pink stage of flower development.

Expt. 4, bloom and postbloom thinners, 'Delicious'. Sixty-four mature 'Ace Delicious'/M.26 were selected. Limbs were tagged, blossom clusters counted before full bloom, and trees were blocked into eight groups (replications) containing eight trees each, similar to that described in Expt. 1. On two trees in each replication, sulcarbamide (monocarbamide dihydrogen sulfate, Wilthin; Entek Corp., Brea, CA) at 3.75

mL·L⁻¹ with 0.1% (v/v) Regulaid was sprayed on 19 May (80% bloom). On 23 May (PF), two trees in each block received a spray of 900 mg·L⁻¹ carbaryl. Also at PF, two trees that previously received a bloom spray of sulcarbamide and two trees that were previously unsprayed received a spray of 8 mg·L⁻¹ NAA plus 900 mg·L⁻¹ carbaryl. When average fruit size reached 8.1 mm on 31 May, the two trees that previously were sprayed with 900 mg·L⁻¹ carbaryl at PF also received a spray of 75 mg·L⁻¹ benzyladenine (BA as the Accel formulation; Valent Bio-Sciences Corp., Libertyville, IL) plus 900 mg·L⁻¹ carbaryl. All sprays treatments were applied with a commercial airblast sprayer delivering a TRV dilute volume of 1168 L·ha⁻¹. Fruit set was assessed at the end of June drop in July by counting all persisting fruit on tagged limbs. At the normal time of harvest, 30 fruit were randomly harvested from the periphery of the tree and then taken to the laboratory where they were weighed.

Statistical analysis. Statistical analysis was done using analysis of variance to determine significance of treatments. When appropriate, means were separated by orthogonal polynomial comparison or regression analysis.

Results

Expt. 1, prohexadione-calcium concentration, 'McIntosh'. ProCa increased fruit set on McIntosh apples (Table 1). The response was significant when expressed as either fruit per centimeter squared limb cross-sectional area or as percent fruit set. Two applications of ProCa at 125 mg·L⁻¹ spaced 4 weeks apart were no more effective at increasing fruit set than one application made when shoots were ≈8 cm in length. Return bloom on ProCa-treated trees was reduced linearly with increasing concentration. Return bloom on trees that received 125 mg·L⁻¹ ProCa was comparable regardless of whether they received one or two applications.

Expt. 2, naphthaleneacetic acid timing, 'McIntosh'. The purpose of this experiment was to determine if the time of thinner application (NAA) relative to the application of ProCa had any influence on thinning ProCa-treated trees. The later that NAA was applied, the greater the reduction in fruit set (Table 2). ProCa increased fruit set and regardless of the timing of NAA application, the set on ProCa-treated trees, expressed as percent set, had greater fruit set than on trees not receiving ProCa. When fruit set is expressed as fruit per 100 blossom clusters, all trees receiving ProCa, regardless of thinning treatment, had greater fruit set. When fruit set is expressed as fruit per centimeter squared limb cross-section area, ProCa-treated trees had greater set except for trees treated with NAA when fruit size averaged 8.7 mm on 31 May. There was a ProCa × NAA interaction. Although ProCa always increased fruit set within an NAA timing, the differences were less with the untreated control and with the late NAA application at

13.8 mm. Fruit weight on all trees receiving ProCa was lower than on trees that received no ProCa.

Expt. 3, thinning combinations, 'Delicious'. Fruit set on trees that received ProCa was greater than on untreated trees (Table 3). In most instances, but not all, reduction in crop load on ProCa-treated trees was less than on trees that received just the chemical thinner treatment. In this experiment, ProCa alone did not increase fruit set relative to trees that received no chemical thinner spray (control). Fruit weight on trees receiving ProCa was less than on untreated control trees or on trees that received the corresponding chemical thinner treatment. There was a thinner × ProCa interaction for fruit weight. Both thinner treatments and ProCa increased the number of pygmy fruit, but the greatest increase was realized when thinners were applied on ProCa-treated trees. Chemical thinner treatments increased return bloom, whereas ProCa had no influence.

Expt. 4, bloom and postbloom thinners, 'Delicious'. ProCa increased fruit set on 'Delicious' (Table 4). In all instances, chemical thinner combinations significantly reduced fruit set. The only instance when fruit set was similar between ProCa-treated and untreated trees was when carbaryl was applied at bloom followed by BA plus carbaryl at 8.1 mm. However, this treatment was too aggressive and crop load was reduced to 50% of the target full crop. There was a thinner × ProCa interaction for fruit weight, which can be attributed to the previously mentioned thinning treatment. ProCa significantly reduced fruit size, but when thinners were applied to ProCa-treated trees, fruit size was increased more than if no thinner was used.

Discussion

Evidence in the literature to support the suggestions that ProCa increases fruit set is conflicting. Several reports document increased fruit set after ProCa applications (Byers et al., 2004; Glenn and Miller, 2005; Greene, 1999), whereas others report no effect on fruit set/yield (Byers and Yoder, 1999; Costa et al., 2000; Miller, 2002). Medjdoub et al. (2005) reported that ProCa increased fruit set on 'Gala' but not on 'Fuji'. In this investigation, ProCa increased fruit set significantly in three of the four experiments reported, except in instances in which aggressive treatments caused excessive thinning. In the fourth experiment in which ProCa did not increase fruit set, it did reduce the efficacy of the applied thinners. Therefore, crop load management of trees that are treated with ProCa must be managed differently than those that receive no ProCa for growth control or fire blight control. One of the major objectives of this study was to determine how consistently ProCa influenced fruit set when used according to directions on the ProCa label.

A critical component for the effective use of ProCa for growth control and fire blight control is early application near PF

Table 1. Effect of prohexadione-calcium (ProCa) on fruit set and terminal growth of mature McIntosh apples (Expt. 1).

Treatment mg·L ⁻¹	Date of application	Blossom clusters/cm ² LCSA ^z	Fruit set		Terminal growth (cm)	Return bloom Blossom clusters/cm ² LCSA
			Fruit/cm LCSA	Fruit percent set		
1 Control		9.0	4.2	46	40.3	11.9
2 ProCa 125	31 May	9.0	7.4	83	27.5	8.5
3 ProCa 250	31 May	9.2	7.4	82	26.7	8.0
4 ProCa 125 + ProCa 125	31 May and 28 June	9.1	6.7	74	27.9	10.6
Significance						
ProCa		NS	1**	1***	1***	1**
ProCa 1× vs. ProCa 2×		NS	NS	NS	NS	NS

^zLCSA = limb cross-sectional area.NS, **, ***Nonsignificant or significant at $P = 0.01$ or 0.001 , respectively. 1 = linear.Table 2. Effect of prohexadione-calcium (ProCa) and time of 10 mg·L⁻¹ naphthaleneacetic acid (NAA) application on fruit set and fruit size of McIntosh apples (Expt. 2).

Treatment mg·L ⁻¹	Application		Bloom clusters/cm ² LCSA ^z	Fruit set		Fruit wt (g)
	Date	Fruit size/shoot length/stage		Fruit/cm LCSA	Fruit/100 blossom clusters	
1 Control	—	—	9.6	7.5	80	120
2 ProCa 250	31 May	11.7 cm	10.3	10.6	105	107
3 NAA 10	23 May	PF	9.4	5.1	55	138
4 NAA 10	23 May	PF	10.0	7.5	75	120
ProCa 250	31 May	11.7 cm				
5 NAA 10	31 May	8.7 mm	9.9	5.0	50	131
6 NAA 10	31 May	8.7 mm	10.0	6.1	63	115
ProCa 250	31 May	11.7 cm				
7 NAA 10	6 June	13.8 mm	9.6	2.3	26	128
8 NAA 10	6 June	13.8 mm	9.9	5.9	62	115
ProCa 250	31 May	11.7 cm				
Significance						
NAA			NS	1***	1***	1*
ProCa			NS	***	***	***
NAA × ProCa			NS	*	*	**
T1 vs. T2			NS	***	***	**
T3 vs. T4			NS	**	**	***
T5 vs. T6			NS	NS	*	***
T7 vs. T8			NS	***	***	**

^zLCSA = limb cross-sectional area.NS, **, ***Nonsignificant or significant at $P = 0.05$, 0.01 , or 0.001 , respectively; 1 = linear.

Table 3. Effect of prohexadione-calcium (ProCa) and naphthaleneacetic acid (NAA) and carbaryl thinning treatments on fruit set of Ace Delicious apples (Expt. 3).

Treatment mg·L ⁻¹	Application		Blossom clusters/cm ² LCSA ^z	Fruit set		Fruit wt (g)	Pygmy fruit (%)	Return bloom blossom clusters/cm ² LCSA
	Date	Fruit size/shoot length/stage		Fruit/cm LCSA	Percent set			
1 Control	—	—	6.6	7.0	113	169	1.3	2.6
2 ProCa 250	2 June	9.0 cm	6.6	7.8	126	144	9.0	3.7
3 NAA 10 + carbaryl 600	26 May	PF + 2 d	6.4	2.2	39	225	1.6	7.3
NAA 8	2 June	9.6 mm						
4 NAA 10 + carbaryl 600	26 May	PF + 2 d	6.8	3.9	60	195	4.1	6.7
NAA 8	2 June	9.6 mm						
ProCa 250	2 June	9 cm						
5 NAA 8	2 June	9.6 mm	6.0	3.9	71	199	1.3	5.5
6 NAA 8	2 June	9.6 mm	6.2	6.2	118	152	10.6	3.9
ProCa 250	2 June	9.0 cm						
7 NAA 8 + carbaryl 600	2 June	9.6 mm	6.3	2.1	36	225	4.7	7.4
8 NAA 8 + carbaryl 600	2 June	9.6 mm	6.7	3.9	70	152	13.4	5.9
ProCa 250	2 June	9.0 cm						
Significance								
ProCa			NS	***	***	***	*	NS
Thinning			NS	***	***	***	***	***
ProCa × thinning			NS	NS	NS	*	NS	NS
T1 vs. T2			NS	NS	NS	*	**	NS
T3 vs. T4			NS	*	NS	**	NS	NS
T5 vs. T6			NS	***	***	***	**	NS
T7 vs. T8			NS	**	**	***	**	NS

^zLCSA = limb cross-section area.NS, **, ***Nonsignificant or significant at $P = 0.05$, 0.01 , or 0.001 , respectively.

PF = petal fall.

Table 4. Effect of prohexadione-calcium (ProCa) and chemical thinning treatments of fruit set and fruit weight of Ace Delicious apples (Expt. 4).

Treatment mg·L ⁻¹	Application		Bloom blossom clusters/cm ² LCSA ^z	Fruit set		Fruit wt (g)
	Date	Fruit size/shoot length/stage		Fruit/cm ² LCSA	Fruit/100 blossom clusters	
1 Control	—	—	8.4	5.1	61	226
2 ProCa 250	31 May	8.4 cm	8.4	6.5	87	165
3 NAA 8 + carbaryl 900	23 May	PF	8.8	4.1	50	226
NAA 8 + carbaryl 900	31 May	8.1 mm				
4 NAA 8 + carbaryl 900	23 May	PF	8.5	5.5	70	172
NAA 8 + carbaryl 900	31 May	8.1 mm				
ProCa 250	31 May	8.4 cm				
5 Wilthin 3.75 mg·L ⁻¹	19 May	80% bloom	8.2	2.8	35	276
NAA 8 + carbaryl 900	23 May	PF				
6 Wilthin 3.75 mg·L ⁻¹	19 May	80% bloom	8.7	4.8	54	198
NAA 8 + carbaryl 900	23 May	PF				
ProCa 250	31 May	8.4 cm				
7 Carbaryl 900	23 May	PF	8.3	2.7	35	233
BA 75 + carbaryl 900	31 May	8.1 mm				
8 Carbaryl 900	23 May	PF	8.3	2.6	35	214
BA 75 + carbaryl 900	31 May	8.1 mm				
ProCa 250	31 May	8.4 cm				
Significance						
ProCa			NS	***	***	***
Thinning			NS	***	***	***
ProCa × thinning			NS	NS	NS	**
T1 vs. T2			NS	*	**	***
T3 vs. T4			NS	*	*	***
T5 vs. T6			NS	**	*	***
T7 vs. T8			NS	NS	NS	NS

^z LCSA = limb cross-section area.NS, *, **, ***Nonsignificant or significant at *P* = 0.05, 0.01, or 0.001, respectively.

BA = benzyladenine; PF = petal fall.

(Rademacher and Kober, 2003). Earlier application is not recommended because ProCa is taken up primarily by the leaves and sufficient leaf area does not develop until terminal shoot growth reaches 2 to 5 cm, which is often between full bloom and PF (Miller, 2002; Rademacher and Kober, 2003). Later application of ProCa is equally inadvisable because the majority of terminal growth on apples occurs during the 3 to 4 weeks after bloom and it requires 10 to 14 d for growth control and metabolic changes to take place (Byers and Yoder, 1999; Unrath, 1999). This creates a dilemma because PF application of ProCa appears to be responsible for increased fruit set (Unrath, 1999). Therefore, a strategy other than altering the time of application will be necessary to ameliorate effects on fruit set and for efficient regulation of crop load.

There appears that there may be a direct positive relationship between the amount of ProCa applied and increased fruit set. Therefore, a potential way to reduce the impact of ProCa on fruit set may be to use lower rates, especially with the first application. The effect of using lower rates of ProCa on terminal growth is currently being evaluated in several locations in the United States, and using lower rates in the initial application has been espoused by Rademacher and Kober (2003). Norelli and Miller (2004) reported that enhancement of fire blight resistance by ProCa in West Virginia was related to suppression of shoot growth at the time of inoculation, and the resistance response was linearly related to the amount of ProCa applied. Suppression of growth in cooler northern regions of the United States may

require less ProCa than in warmer regions where vegetative growth is traditionally more vigorous. Thus, in the northern United States, good fire blight suppression may be possible with lower ProCa rates. This possibility is currently under investigation.

Several thinning strategies were used in this investigation, which included applying thinners before, at the time of, or after ProCa application. Bloom and postbloom thinners and thinning combinations of varying strength were also used. Regardless of the thinning strategy used, crop load was generally greater on trees treated with ProCa compared with trees that did not receive ProCa. Even on trees in which ProCa did not increase set ('Delicious', Expt. 3), treated trees did not thin to the extent that untreated trees did. In all thinning experiments, the most aggressive thinning combinations did overthin, even on ProCa-treated trees. The thinning strategy used in an orchard is generally arrived at after considering many factors, including the cultivar, tree age, orchard fruit set history, bloom and potential crop load, and, most importantly, the predicted weather for several days after application (Greene, 2002b). After arriving at the thinning strategy that seems appropriate for an untreated tree, one should then add at least one more thinning component to enhance thinning activity if the orchard was treated with ProCa. This additional component may include application of a PF spray if none was planned or the addition of another or different thinner at one of the timings. An approach that is not suggested is to increase the concentration of an individual thinner, because the response to a thinner is often not linear.

In some instances, application of thinners, especially naphthaleneacetamide and to a lesser extent NAA, can cause pygmy fruit formation on 'Delicious' (Williams and Edgerton, 1981). There appeared to be a small increase in pygmy formation in Expt. 3. However, there was a much greater increase in pygmy fruit incited by ProCa, and this is the first time that ProCa has been implicated for increasing pygmy fruit formation. When NAA + carbaryl was applied 2 d after PF and 7 d before ProCa, pygmy fruit were not formed.

It is widely acknowledged that there is usually an inverse relationship between fruit set and fruit size. Therefore, it is not surprising in this investigation that increases in fruit set as the result of ProCa application did result in decreased fruit size. Similarly, Glenn and Miller (2005) and Medjdoub et al. (2005) reported that increases in fruit set as a result of ProCa application resulted in reduced fruit size. In Expt. 3, fruit set on ProCa-treated trees and control trees was similar, yet fruit weight from trees treated with ProCa was 15% less. The ProCa treatment did increase pygmy fruit numbers, but these fruit were not included when average fruit weight was calculated. Miller (2007) has also observed that ProCa did reduce fruit weight in commercial orchards, although it appeared that there was no difference in fruit set. In these instances, high rates of ProCa may be implicated, and at least partially responsible. Strategies that involve using lower rates of ProCa may reduce or eliminate the direct effect of ProCa on reducing fruit size. This strategy was suggested by Rademacher and Kober (2003).

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