Postharvest Quality of Cut Roses Following Electron-beam Irradiation

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Abstract. Cut *Rosa ×hybrida* L. 'Royalty' flowers were used to determine the efficacy of electron-beam irradiation for increasing postharvest quality and decreasing petal infection by *Botrytis cinerea* Pers. In an experiment for determining the injury threshold, roses received electron-beam irradiation of 0, 0.5, 1, 2, and 4 kGy. Irradiation dosages ≥ 1 kGy caused necrosis on petal tissue and decreased postharvest life at 20 °C. In a second experiment to evaluate postharvest quality, roses were irradiated at 0, 0.25, 0.5, 0.75, and 1 kGy. Dosages of 0.25 and 0.5 kGy slowed the rate of flower bud opening for 2 days but did not decrease postharvest quality when compared with nonirradiated roses. Roses that received irradiation dosages of 0.75 and 1 kGy showed unacceptable quality. In a third experiment, roses that had or had not been inoculated with *B. cinerea* were irradiated at 0, 0.25, 0.5, and 0.75 kGy. Irradiation did not control *B. cinerea* populations, and rose quality decreased as dosage increased. In a fourth experiment to determine the effect of irradiation on *B. cinerea*, conidia on water-agar plates exposed to dosages $\leq 1, 2$, and 4 kGy germinated at rates of $\approx 90\%$, 33%, and 2%, respectively, within 24 h.

Gamma rays from ^{60}Co , in combination with refrigeration, extended the shelf life of strawberries (*Fragaria ×ananassa* Duch.) by elimination of *Botrytis cinerea* Pers. (Institute of Food Technologists, 1983; World Health Organization, 1988). Kohl (1967) evaluated postharvest development and quality of cut roses exposed to gamma rays from ^{60}Co at doses of 0.1 to 2.0 kGy (10 to 200 krad were reported). However, to our knowledge, no information is available on the efficacy of electron-beam irradiation for extending the postharvest life of roses or for reducing microbial populations on roses.

Botrytis cinerea is a serious fungal pathogen on many ornamental crops, including roses (Hammer and Marois, 1989; Jarvis and Slingby, 1975). Many commodities are contaminated with latent infections of *B. cinerea* at harvest, and lesions develop rapidly under moist conditions during storage and shipment, even at 0 °C (Hammer and Marois, 1989; Sommer and Fortlage, 1966). Growers, wholesalers, and retailers contend with this ubiquitous microorganism by using fungicides to prevent postharvest development of infections. Relatively few fungicides are registered for *B. cinerea* control, and repeated use of fungicides may lead to fungicide-resistant *B. cinerea* strains (Jarvis and Slingby, 1975; Moorman, 1995; Moorman et al., 1989). In addition, unsightly chemical residues on the crops, the risk of environmental contamination, health hazards for applicators, and increasingly stringent regulation of pesticide use and disposal (Hammer and Marois, 1989) are problems that should be considered seriously when fungicides are used. Thus, nonchemical control methods need to be developed.

The three main types of irradiation sources are gamma rays from radioactive ^{60}Co or ^{137}Cs , X-rays, and high-energy electrons (Council for Agricultural Science and Technology, 1989; Morrison, 1989). Irradiation by using electrons offers two benefits not available when gamma rays are used; these include a nonradioactive irradiation source and the fact that

electron-beam irradiation can be accomplished at a much greater dose-rate that may reduce the potential for tissue damage by allowing less residence time in the irradiation facility (Council for Agricultural Science and Technology, 1989).

Irradiation can damage living cells, and its use requires determination of the dosage that provides maximum inactivation of unwanted species, such as *B. cinerea*, without reducing postharvest quality. Thus, determination of an appropriate dosage will depend upon the radiation susceptibility of the fungus, or other pathogenic species, and the resistance of the crop to undesirable radiation injury (Sommer et al., 1964). The purpose of our research was to investigate the effects of electron-beam irradiation for simultaneously increasing postharvest quality and decreasing petal infection by *B. cinerea* on cut flowers of *Rosa ×hybrida* L. 'Royalty'. The specific objectives were to determine dosages of electron-beam irradiation that do not damage rose tissues (injury threshold), to characterize postharvest quality of irradiated cut roses, and to determine if electron-beam irradiation can reduce naturally occurring and inoculated populations of *B. cinerea* on petals of cut roses.

Materials and Methods

Experiment design. Cut flowers of 'Royalty' roses produced at Len Busch Roses, Inc., Plymouth, Minn., were used for all experiments. A randomized complete-block design was used for all experiments. Those conducted at different times of the year were designated as blocks to account for possible seasonal variation in rose quality and in microflora on rose petals. Each repetition (block) of each experiment contained four replications per treatment.

Injury threshold experiment. This experiment was conducted twice. Rose stems were recut to 46 cm from the distal end of the bud, randomly subdivided into groups of five stems, and wrapped (bundled) in cellophane sleeves. Bundles were irradiated at the Electron Beam Linear Accelerator Facility at Iowa State Univ. There were six treatments and four replications (each = one group of five bundled roses) within a block. Controls included one treatment that remained in the laboratory and another that passed through the irradiation facility but received 0 kGy. The other irradiation dosages were 0.5, 1, 2, and 4 kGy at a dose rate of 45 kGy·min⁻¹. All irradiations were conducted with an electron beam at 10 MeV. After irradiation, stems were recut to 40 cm below the receptacle, and all leaves, except the upper two, were removed. Replications were weighed and placed in 1-L mason jars that contained 500 mL of preservative solution of deionized water; 1% dextrose; and 80 mg·L⁻¹ citric acid monohydrate, 4 mg·L⁻¹ sodium hypochlorite (from bleach), and 60 mg·L⁻¹ 8-hydroxyquinoline citrate. Preservative solution pH ranged from 3.2 to 3.5. Preservative solution was replaced every 5 days, and the amount absorbed was recorded. During postirradiation holding, roses received 12 h of irradiance per

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day at $\approx 14 \mu\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$ photosynthetically active radiation (PAR) from cool-white fluorescent lamps, and the air temperature in the holding room was $20.5 \pm 0.5^\circ\text{C}$. Daily fresh mass and preservative solution absorption were recorded for each replication during the 10-day evaluation period. Flowers with $\geq 10\%$ fresh mass loss from the initial mass were considered to be at the end of vase life (Rogers, 1962).

Postharvest quality evaluation experiment. This experiment was conducted three times. A nontreated control that remained in the laboratory and irradiation dosages of 0, 0.25, 0.5, 0.75, and 1 kGy at a dose rate of $15 \text{ kGy}\cdot\text{min}^{-1}$ were used. The lower dose rate in this experiment was necessary to achieve irradiation at a dosage of 0.25 kGy. The same procedures and holding room conditions were used as in the injury threshold experiment. Data recorded during the 10-day evaluation period included daily fresh mass, preservative solution absorption, days until loss of petal turgidity, percentage of bent-neck flowers, daily flower diameter (as measured on a rating scale of 1 to 10 where 1 = less than or equal to 13 mm and 10 = greater than 100 mm), maximum flower diameter, and days to reach maximum flower diameter.

Irradiation of roses inoculated with *B. cinerea*. Preliminary experiments were conducted to determine an appropriate inoculum concentration and interval between inoculation and irradiation. This experiment was conducted twice. A factorial combination of noninoculated and inoculated roses with irradiation dosages of 0, 0.25, 0.5, and 0.75 kGy at a dose rate of $15 \text{ kGy}\cdot\text{min}^{-1}$ was used. An isolate of *B. cinerea* was obtained from each of three rose cultivars, each one grown in a different greenhouse. Isolates were grown on potato-dextrose agar in a growth chamber at $21 \pm 1^\circ\text{C}$ with 12 h of $100 \pm 10 \mu\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$ PAR per day from cool-white fluorescent lamps. Conidia from 14-day-old cultures of each isolate were washed with sterile, deionized water amended with Tween 20 (1 drop/100 mL) and combined in equal volumes. Stems were recut to 40 cm from the tip of the bud and arranged with flower buds inside 20×80 -cm rectangles on paper. For noninoculated controls, buds within each rectangle were sprayed with 20 mL sterile, deionized water with an artist's airbrush (model no. 5715; Devilbiss, Somerset, Pa.) operated at 176 kPa from a distance of 20 cm. Roses were allowed to dry and were wrapped in groups of six stems in cellophane sleeves. For inoculated roses, 20 mL of a suspension of *B. cinerea* (≈ 300 conidia/mL) was applied to each rectangle. Roses received irradiation at 0, 0.25, 0.5, and 0.75 kGy. After irradiation, flowers were transported to the laboratory and the basipetal 2 cm of each stem was removed. Bundles of six flowers were set in a holding solution (same components as in previous experiments but without dextrose) in a cooler for 1 h at $2 \pm 0.5^\circ\text{C}$. Glass chambers ($7.7 \times 10^{-3} \text{ m}^3$ each) also were held similarly to minimize water condensation on petals. After 1 h of cooling, each rose bundle in preservative solution was placed in one of the glass

chambers that then were sealed and stored in darkness for 7 days at $2 \pm 0.5^\circ\text{C}$. After the 7-day storage period, three of the six stems in each bundle were chosen at random for lesion counts per rose 24 h after their removal from storage. The other three rose stems in the same bundle were recut to 30 cm below the receptacle and their vase life and quality were evaluated over 10 days. The same procedure, holding room conditions, and preservative solution were used as in previous experiments. After the 7-day storage period, daily fresh mass, preservative solution absorption, and percentage of bent-neck flowers were recorded during the 10-day evaluation period.

Irradiation of *B. cinerea* conidia. This experiment was conducted once to determine the irradiation dose required to inhibit germination of *B. cinerea* conidia. There were four replications within each treatment (one replication = one petri plate). A spore suspension (0.1 mL volume, 6×10^3 conidia/mL) was spread evenly over water agar in a 100-mm-diameter petri plate. Plates received irradiation at 0, 0.5, 1, 2, and 4 kGy at a dose rate of $45 \text{ kGy}\cdot\text{min}^{-1}$. The percentage of germinated conidia was recorded 24 h after irradiation. A conidium was counted as germinated if it exhibited a germ tube longer than the diameter of the conidium.

Results

Injury threshold. Roses that remained in the laboratory and control roses that received 0 kGy of irradiation displayed nearly identical results for all characteristics; thus, only data for 0 kGy are presented. Time to reach peak fresh mass for each treatment decreased as dosage increased (Fig. 1). Roses irradiated at dosages > 0.5 kGy lost fresh mass faster (Fig. 1), and this loss decreased vase life. Flowers from 0 and 0.5 kGy had a vase life > 10 days. For 1, 2, and 4 kGy, vase life, expressed as $> 10\%$ loss in fresh mass, ended on days 8, 7, and 7, respectively (Fig. 1). The amount of total preservative solution absorbed decreased with increasing irradiation doses (data not presented) and correlated ($r^2 = 0.99$) with the daily fresh mass pattern as expressed by the area under the fresh mass curve (Fig. 1) from day 0 to day 10.

Postharvest quality evaluation. As a result of the data obtained from the injury threshold experiment, we decreased the irradiation dosages to levels that were less injurious to the flowers. Roses that remained in the laboratory and control roses that received 0 kGy of irradiation displayed nearly identical results for all characteristics; thus, only data for 0 kGy are presented. Fresh mass of roses irradiated at 0.5, 0.75, and 1 kGy began to differ from the 0 kGy control on days 8, 6, and 5, respectively (Fig. 2). Fresh mass of roses from 0 and 0.25 kGy did not differ over the entire 10 days of evaluation and never decreased to $\leq 90\%$ of the initial fresh mass. For the 0.5, 0.75, and 1 kGy doses, vase life ended on days 10, 8, and 7, respectively (Fig. 2). The amount of total preservative solution absorbed decreased with increasing irradiation doses (Table 1) and cor-

related ($r^2 = 0.98$) with the daily fresh mass pattern as expressed by the area under the fresh mass curve (Fig. 2) from day 0 to day 10. Flowers treated with 0.25 and 0.5 kGy were not different from the 0 kGy control in time to loss of petal turgidity and percentage of bent-neck flowers (Table 1). Roses treated with 0.75 and 1 kGy, however, lost petal turgidity faster and the percentage of bent-neck flowers increased as dosage increased (Table 1). Roses irradiated at ≥ 0.25 kGy had a smaller diameter than control roses during days 1 and 2 after irradiation, but flower diameters showed no difference from the nontreated control by day 3 (Fig. 3). Flowers irradiated with 1 kGy reached their maximum diameter faster (3 days) than flowers in the other treatments (≈ 5 days), but they attained a smaller maximum diameter than flowers exposed to lower doses (Fig. 3).

Irradiation of roses inoculated with *B. cinerea*. Irradiation dosage did not affect the number of lesions per flower (16 to 22 lesions/rose; $P > F = 0.8035$). Inoculated roses had more lesions per flower than noninoculated roses (25 lesions/inoculated rose and 14 lesions/noninoculated rose, respectively; $P > F = 0.0261$). Irradiation dosage affected daily fresh mass and vase life as in the first two experiments (data not presented), but inoculation did not affect either attribute (data not presented). As in the injury threshold experiment, the number of days until peak fresh mass was inversely proportional to irradiation dosage (data not presented). As in the other experiments, the higher the dosage, the faster the roses began to lose fresh mass, which shortened vase life (data not presented). The amount of total preservative solution absorbed decreased with increasing irradiation doses (Table 2) and correlated ($r^2 = 0.99$) with the daily fresh mass pattern as expressed by the area under the fresh mass curve from day 7 to day 17 (data not presented). Flowers that received 0, 0.25, and 0.5 kGy of irradiation showed the same percentage of bent-neck flowers, and flowers that received 0.75 kGy of irradiation exhibited more bent-neck than flowers that received 0 and 0.25 kGy of irradiation (Table 2).

Irradiation of *B. cinerea* conidia. *Botrytis cinerea* conidia irradiated at dosages of 0, 0.5, and 1 kGy germinated at 91%, 89%, and 88%, respectively, whereas dosages of 2 and 4 kGy decreased germination to 33% and 2%, respectively ($P > F = 0.0001$).

Discussion

Roses that received ≥ 0.75 kGy had irreversible petal tissue damage and undesirable appearance. Similar results were found for 'Forever Yours' and 'Happiness' roses irradiated with gamma rays from ^{60}Co at 0.1 to 2.0 kGy (10 to 200 krad were reported) (Kohl, 1967). In our experiments, the estimated acceptable amount of electron-beam irradiation dosage for 'Royalty' roses was ≤ 0.5 kGy when the flowers were held for 10 days at 21°C . It has been estimated that 0.2 kGy was the maximum dosage of ionizing radiation that could

Fig. 1. Injury threshold experiment: Fresh mass of *Rosa x hybrida* 'Royalty' flowers during the 10-day evaluation period for roses exposed to 0 (○), 0.5 (■), 1 (▲), 2 (□), or 4 (✱) kGy of electron-beam irradiation. The line at 100% indicates the initial fresh mass. The end of vase life was the day when fresh mass dropped to or below 90% of the original fresh mass. Data presented are treatment means pooled from two independent repetitions. LSD ($\alpha = 0.05$) was for comparison between treatments on each day only. LSD ($\alpha = 0.05$) = 4.8 for comparison between days for any one irradiation treatment level.

Fig. 2. Postharvest quality evaluation experiment: Fresh mass of *Rosa x hybrida* 'Royalty' flowers during the 10-day evaluation period for roses exposed to 0 (○), 0.25 (■), 0.5 (▲), 0.75 (□), or 1 (✱) kGy of electron-beam irradiation. The line at 100% indicates the initial fresh mass. The end of vase life was the day when fresh mass dropped to or below 90% of the original fresh mass. Data presented are treatment means pooled from three independent repetitions. LSD ($\alpha = 0.05$) was for comparison between treatments on each day only. LSD ($\alpha = 0.05$) = 7.8 for comparison between days for any one irradiation treatment level.

be tolerated by cut flowers, such as *Rosa x hybrida*, *Dianthus caryophyllus* L., *Dendranthema x grandiflora* (Ramat.) Kitamura, and orchids (United Fresh Fruit and Vegetable Association, 1986). These differences in results may have been caused by different application methods, such as types of irradiation source, and differences in species, rose cultivars, or experimental conditions. The maximum tolerable irradiation dosage also depends upon the sensitivity of the plant tissues of different crops to the irradiation dosage. Published tolerable dosages for fruit and vegetables were 0.15 kGy for potato (*Solanum tuberosum* L.) tubers and 2 kGy for strawberries (*Fragaria x ananassa* Duch.) (Council for Agricultural Science and Technology, 1989; Maxie et al., 1971; United Fresh Fruit and Vegetable Association, 1986), and these large differences in tolerable dosage also may apply to flower species.

In our experiments, roses that received 0.25, 0.5, 0.75, or 1 kGy showed a delay in flower opening of ≈ 2 days. Roses treated with 1 kGy remained smaller than control roses treated with 0 kGy. Haasbroek et al. (1973) found that the rate and degree of flower opening of *Protea compacta* R.Br. flowers irradiated with gamma rays decreased with increasing dosages and that irradiation at 0.9 kGy suppressed flower opening almost completely, which is similar to our results. In contrast, irradiation did not affect the rate of opening of *Leucospermum cordifolium* Salisb. flowers (Haasbroek et al., 1973). These disparate findings emphasize that species differ in their level of tolerance to irradiation.

Irradiation with dosages of ≤ 0.75 kGy did not control *B. cinerea* populations on noninoculated or inoculated flowers, and *B. cinerea* conidia tolerated dosages between 1 and 2 kGy. Thus, *B. cinerea* conidia tolerate higher electron-beam dosages than rose tissues can tolerate. Sommer et al. (1964, 1968) also found that ≤ 1 kGy of gamma irradiation minimally inhibited growth of *B. cinerea*. Conidia of *B. cinerea* in vitro were inactivated completely only at dosages > 3 kGy (Ryall and Pentzer, 1982; Sommer et al., 1964). Maxie et al. (1971) showed that the minimum dose of ionizing radiation to inhibit *B. cinerea* on strawberry was 2 kGy. The minimum dose required to produce the desired effect is often more than the commodity can tolerate, and this may limit the commercial application of the irradiation process to control the occurrence of *B. cinerea* on horticultural crops (United Fresh Fruit and Vegetable Association, 1986). Maxie et al. (1971) also mentioned that irradiation is infeasible with most fruit and vegetables because of a lack of a beneficial effect at noninjurious dosages. The fresh mass patterns for noninoculated and inoculated roses were similar to roses used in the postharvest quality evaluation experiment. A slight difference was that roses exposed to 0.25 kGy began to show differences from roses irradiated at 0 kGy 14 days after irradiation. However, there were no differences between roses irradiated at 0 and 0.25 kGy through the entire 10-day postharvest evaluation period (Fig. 2). These

Table 1. Effect of electron-beam irradiation on postharvest quality attributes of *Rosa ×hybrida* 'Royalty' held at 20 °C for 10 days following irradiation. Data presented are treatment means pooled from three independent repetitions.

Dose (kGy)	Total preservative solution absorption (mL)	Time to loss of petal turgidity (days)	Bent-neck flowers (%)
0	592	8.3	12
0.25	517	8.8	5
0.5	443	7.8	18
0.75	372	6.8	42
1	327	4.8	68
P > F	0.0001	0.0001	0.0006

Fig. 3. Postharvest quality evaluation experiment: Flower diameter rating of *Rosa ×hybrida* 'Royalty' flowers during the 10-day evaluation period for roses exposed to 0 (○), 0.25 (■), 0.5 (▲), 0.75 (□), or 1 (✱) kGy of electron-beam irradiation. Means of flower diameters were rated by: 1 = less than or equal to 13 mm, 2 = greater than or equal to 13 mm ≤ 18 mm, 3 = greater than or equal to 18 mm ≤ 25 mm, 4 = greater than or equal to 25 mm ≤ 32 mm, 5 = greater than or equal to 32 mm ≤ 38 mm, 6 = greater than or equal to 38 mm ≤ 50 mm, 7 = greater than or equal to 50 mm ≤ 65 mm, 8 = greater than or equal to 65 mm ≤ 80 mm, 9 = greater than or equal to 80 mm ≤ 100 mm, and 10 = greater than or equal to 100 mm. Data presented are treatment means pooled from three independent repetitions. LSD ($\alpha = 0.05$) was for comparison between treatments on each day only. LSD ($\alpha = 0.05$) = 0.77 for comparison between days for any one irradiation treatment level.

results were different from those of Hammer and Marois (1989), who found many more lesions in inoculated roses, and the higher lesion count caused a greater effect on fresh mass gain and other postharvest quality changes. These differences may have been caused by the additional 7-day storage period, or they may have been caused by slight differences in the inoculation and incubation methodologies.

In our research, electron-beam irradiation at 0.25 and 0.5 kGy temporarily delayed flower opening without decreasing rose quality for 'Royalty' roses held at 21 °C for up to 10 days after irradiation. The delay of ≈ 2 days was lost by day 3 (Fig. 2), which may be a favorable characteristic for wholesale and retail florists because it may give the florist more time to

market the flowers. We have found that electron-beam irradiation was not an effective method for the control of *B. cinerea* on *Rosa ×hybrida* 'Royalty' roses because irradiation damages flower tissue at dosages that do not control *B. cinerea* populations. Although electron-beam irradiation at these dosages does not control *B. cinerea*, the techniques we used and our results may be applicable to investigations of other bacterial or fungal pathogens on cut roses.

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Table 2. Effect of electron-beam irradiation on total preservative solution absorption and development of bent neck of *Rosa ×hybrida* 'Royalty' held at 20 °C for 10 days following electron-beam irradiation and the 7-day storage period at 2 ± 0.5 °C. Data presented are treatment means pooled from two independent repetitions.

Dose (kGy)	Total preservative solution absorption (mL)	Bent-neck flowers (%)
0	317	12
0.25	287	15
0.5	257	21
0.75	230	50
P > F	0.0008	0.0561

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