FORUM

Ionizing Radiation Quarantine Treatments

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Radiação Ionizante em Tratamentos Quarentenários

RESUMO - A irradiação é um tratamento de desinfestação em quarentena viável que tem sido estudado nos últimos 40 anos, embora tenha tido pouco uso comercial. Há dois obstáculos principais à aplicação comercial da irradiação: 1) o fato que os insetos não são mortos imediatamente; e 2) a oposição de consumidores à irradiação, a qual tem sido aceita de certa forma, mas permanecendo o impedimento ao uso comercial em grande escala em função de protocolos de aprovação por agências regulamentadoras de países importadores. O Departamento de Agricultura dos Estados Unidos tem tomado os primeiros passos em permitir o movimento de frutas do Havaí ao resto do país que passaram por tratamento de irradiação. As medidas da eficácia dos tratamentos de desinfestação por irradiação devem incluir prevenção da emergência de adultos, quando apenas ovos e larvas estão presentes, ou esterilidade quando as pupas ou adultos estão presentes. Isto pode ser conseguido pelo uso de doses baixas as quais são toleradas por muitas frutas para pragas como moscas tefritídeas, besouros curculionídeos, e alguns Homoptera. Lepidoptera necessitam de doses moderadamente altas. O estágio mais tolerante à radiação é usualmente o mais avançado em seu desenvolvimento. As fêmeas de insetos são mais suscetíveis a radiação que induz esterilidade; alguns ácaros fêmeas (Tetranychidae) são mais tolerantes que os machos. Pesquisas futuras devem se concentrar em confirmar as doses dos tratamentos quarentenários para outras espécies de insetos (isto só tem sido feito para vários tefritídeos); determinar doses para alguns grupos importantes de organismos para os quais pesquisas insuficientes foram conduzidas (Mollusca, Coccoidea, Thysanoptera, Eriophyidae), e identificar e quantificar fatores de radiação modificantes.

PALAVRAS-CHAVE: Insecta, Arachnida, radiação gama, irradiação, desinfestação pós-colheita.

ABSTRACT- Irradiation is a viable quarantine disinfestation treatment which has been studied for 40 years although it has received very little commercial use. Two principal obstacles to commercial application, 1) the fact that insects are not killed immediately, and 2) consumer opposition to irradiation, have been allayed to some extent, but the remaining impediment to large-scale commercial use is development of approved protocols by government regulatory agencies in importing countries. The United States Department of Agriculture has taken the first step by allowing for the movement of a number of quarantined fruits from Hawaii to the rest of the country following irradiation treatment. The measures of efficacy of irradiation disinfestation treatments should be prevention of adult emergence, when only eggs and larvae are present or sterility when pupae or adults are present. This can be accomplished with relatively low doses that are tolerated by many fruits for such pest groups as tephritid fruit flies, curculionid weevils, and some Homoptera. Lepidoptera will require moderately higher doses. The most radiation-tolerant stage is usually the most advanced one present. Female insects are more susceptible to radiation-induced sterility than males; some spider mite (Tetranychidae) females are more tolerant than males. Future research should concentrate on confirming quarantine treatment doses for more insects (this has only been done for several tephritids), arriving at doses for some important groups of organisms for which scant research has been done (Mollusca, Coccoidea, Thysanoptera, Eriophyidae), and identifying and quantifying radiation-modifying factors.

KEY WORDS: Insecta, Arachnida, gamma radiation, irradiation, postharvest disinfestation.

Quarantines are in place throughout the world to prevent the spread of exotic pests. Nevertheless, materials that may harbor these organisms must often be traded across quarantine boundaries because economic demand for these products exists in areas that are threatened by the pests. When there is an unacceptable risk that a fresh commodity may contain quarantined pests and sufficient evidence exists that a postharvest treatment may kill any quarantined pests present, an importing regulatory agency may allow importation of the commodity if the designated treatment is done according to established protocol. Traditional quarantine treatments have involved one to many hours of temperatures in the range of 43-48°C, from 12 days to several weeks at temperatures between 0-3°C, or a few hours of fumigation with products such as ethylene dibromide or methyl bromide. However, changes in international commerce have created the need for alternative quarantine treatments. Ethylene dibromide was banned 15 years ago because it was considered carcinogenic. Continued use of methyl bromide may be lost in the near future because it is regarded to be a stratospheric ozone depleting substance. Cold treatments are lengthy, phytotoxic to some tropical fruits, and susceptible to power interruptions. Also, the rapid transportation systems of today prefer shorter treatments. Heat treatments are damaging to many fruits such as stone fruits, pomes, and avocados. Although hot water immersion is used extensively for mangoes, some damage to the commodity is suffered and less damaging alternatives are sought. Irradiation is a quarantine treatment which has been studied for 40 years, but only applied on a very limited scale recently. Irradiation promises rapid, efficacious quarantine treatments for many pests while causing minimal damage to commodity quality.

A brief history of research on irradiation as a quarantine treatment is given by Burditt, Jr. (1994). Although the process was first conceived by Koidsumi (1930), the first commercial demonstration of irradiation as a quarantine treatment was not done until 1986 when a shipment of mangoes from Puerto Rico was irradiated with 0.75 kGy and sold in Florida. This was a pilot program to look for alternatives to ethylene dibromide. However, hot water immersion was developed to treat mangoes. In April, 1995 limited shipments of Hawaiian-grown fruits began to be shipped to the Chicago, Illinois area for irradiation and distribution to vendors (Wong 1998). This practice continues today as the only commercial use of irradiation as a quarantine treatment.

Application of Irradiation

There are four sources of ionizing radiation for use on food: gamma irradiation using the isotope of 1) cobalt 60 or 2) cesium 137, 3) electron beam (beta particles), or 4) X-ray (bremsstrahlung) radiation produced when an electron beam strikes a converter, which can be any of a number of high density materials. Bremsstrahlung radiation is very similar to gamma ray from isotopes; both can penetrate pallet-loads of produce. A major difference is that bremsstrahlung radiation is concentrated in the same direction as the electron beam; gamma rays from isotopes are emitted in all directions uniformly (isotropic). Electron beam radiation only penetrates a few centimeters, and, thus, its use is limited to small products passing the irradiation source on a conveyor line. Irradiation dose is measured in gray (Gy), which is joules per kilogram. (the discontinued unit is the rad, which equals 0.01 Gy.) Absorbed dose is what is reported, and it is the amount of ionizing radiation energy imparted on the material being irradiated.

Two different logistical strategies have been developed for commercial gamma irradiation: 1) A chamber is loaded with the materials to be irradiated and the radioactive source is raised into the chamber for the appropriate amount of time to achieve the required absorbed dose. 2) A conveyor system carries the materials to be irradiated past the exposed source at a speed which will give the required absorbed dose. The unidirectional nature of electron beam and bremsstrahlung radiation require that they be applied in a conveyor system.

Research Irradiators

Large-scale commercial irradiators are generally not useful for conducting dosage-determining research because of the difference between the maximum and minimum absorbed doses received (up to a 3:1 dose uniformity ratio). Research to determine the minimum absorbed dose required for an irradiation quarantine treatment is best conducted with small irradiators, such as a Husman Model 521A (Isomedix, Inc., Whippany, NJ, USA) or Gammacell 220 (MDS Nordion, Kanata, Ontario, Canada) which have at worst a 1.25:1 dose uniformity ratio. These irradiators have a circular array of radioactive-source pencils in the middle of which the product to be irradiated sits. Within these irradiators one can use the centerline or other definable, consistent portion of the irradiator chamber to reduce the dose uniformity ratio even further.

Dosimetry

As with any treatment, dosimetry is a crucial component of research and application. Irradiation dosimetry is not intuitive as it is with other treatments such as temperature. The irradiator must undergo reference standard dosimetry when it is set up and whenever major modifications are made to the source or apparatus; this is usually performed by the manufacturer. Routine dosimetry must be performed periodically when using an irradiator. Changes in the type, quantity, density, geometry, or arrangement of the product to be irradiated may result in changes in absorbed dose. Radiochromic film (ISP Technologies, Inc., Wayne, NJ, USA) read with a spectrophotometer and properly calibrated to internationally recognized and traceable standards is an acceptable dosimetry system for routine quarantine treatment research. The American Society for Testing and Materials (West Conshohocken, MD, USA) maintains an international subcommittee devoted to dosimetry for radiation processing whose published standards enjoy high regard. Brazilian members include Dr. Linda V. E. Caldas, IPEN-CNEN, São Paulo and Prof. K. E. Collins, Univ. Estadual de Campinas. One guide is particularly recommended for those doing irradiation quarantine treatment research: E1900 (1997) *Guide for dosimetry in radiation research on food and agricultural products.*

Efficacy of Irradiation Quarantine Treatments

The objective of all quarantine treatments except irradiation is rapid mortality. Irradiation doses needed to cause rapid mortality reduce the quality of fresh commodities. For example, sweetpotato weevil, *Cylas formicarius elegantulus* (Summers), adults irradiated with 1 kGy lived up to 10 days (Dawes *et al*. 1987). Even if 1 kGy were sufficient for a sweetpotato weevil quarantine treatment based on adult mortality, sweetpotatoes cannot tolerate 0.4 kGy without significant negative discoloration of the cooked roots (McGuire & Sharp 1995).

The ultimate objective of a quarantine treatment is to prevent the establishment of exotic pests. Therefore, it is not necessary to kill the pests as long as they can be prevented from developing to the adult stage or prevented from reproducing. Irradiation can accomplish this with relatively low doses tolerated by many fresh commodities. For example, although sweetpotato weevils were not killed rapidly by 1 kGy, females were sterilized by 0.2 kGy (Dawes *et al*. 1987). When developing a quarantine treatment, one should concentrate on the most tolerant stage present in the commodity. In general, as an organism develops it increases in tolerance to irradiation (Table 1). Therefore, the most radiation-tolerant stage will be the most developed one found in the commodity. Table 2 recommends objectives for irradiation quarantine treatments based on the most advanced stage present at the time of harvest. Some insects, such as Fuller rose beetle, *Asynonychus godmani* Crotch, may only be of concern in the egg stage (Johnson *et al*. 1990). Only tephritid fruit fly eggs and larvae are found in fruits; normally pupae and adults are of no concern. However, because commodities are usually irradiated after being packed and some, such as citrus, may sit at ambient temperatures for a few days before being irradiated, it is conceivable that fruit fly pupae, which are more tolerant of irradiation than larvae, may be present in the packing material before the lot is irradiated (Hallman & Worley 1998). Some Lepidoptera, such as pyralids and tortricids, pupate within the commodity. A very high dose of radiation is needed to prevent adult emergence from pupae late in development. Therefore, the objective in this case should be sterility of the emerging adults. In many groups of quarantined arthropods (Acari, Homoptera, Hemiptera, Thysanoptera, and Coleoptera) all stages including actively reproducing adults may be present. Therefore, the only possibility for an irradiation quarantine treatment (given that acute mortality of adults requires very high doses) in these cases is sterility.

Brower and Tilton (1985) present irradiation doses needed to sterilize adults of both sexes of 27 stored product Coleoptera and four Lepidoptera. In all cases save one they found that females were equally or more susceptible to radiation-induced sterility than males. The exception was the dermestid *Anthrenus flavipes* LeConte; while males were sterilized with 50 Gy, females required 80 Gy. Adult female sterility with plant-infesting insects is

Table 1. Dose to achieve 100% adult mortality of cowpea weevil, *Callosobruchus maculatus* (F.), irradiated at different life stages (after Diop *et al*. 1997)

Stage	Dose (Gy)
Egg	20
7 day-old larva	20
15 day-old larva	30
21 day-old larva	60
Pupa	140
Flightless adult	1,500[1]
Flight-able adult	>2,000[1]

[1]Mortality within 48 hours.

Table 2. Recommended objectives of irradiation quarantine treatments based on most advanced insect stage found at time of treatment.

Most advanced stage	Objective of treatment
Egg	Prevent development beyond first instar
Early instars (simple metamorphosis)	Prevent late instar or adult development
Early instars (complete metamorphosis)	Prevent pupariation or pupation
Late instars	Prevent pupation or adult emergence
Pupa	Adult sterility
Adult	Sterility

also achieved with equal or lower doses than male sterility (Table 3). Another exception is Sharp (1995) who, contradicting Dawes *et al*. (1987), found that sweetpotato weevil adult females required 300 Gy to sterilize while males required only 150. Tephritid fruit fly females are sterilized with lower doses applied to late pharate adults than males when both are irradiated for sterile insect release (Hooper 1989). The fact that female insect reproduction is the more susceptible to irradiation of the two sexes is fortunate because research need concentrate only on sterilizing the female regardless of whether it has already mated. The reason that male reproduction is usually more tolerant of irradiation than female reproduction in insects may be due to that fact that the egg is more complex, and, therefore, more susceptible to radiation damage, or it may simply be an artifact of disproportionate numbers. For example, 99.99% sterility means few eggs will survive while relatively many sperm will.

Except for *Tetranychus urticae* Koch, female tetranychid mites are more tolerant of irradiation sterility than males (Table 3). Perhaps this is related to parthenogenesis; unfortunately, there are as yet no examples on radiation-induced sterility of parthenogenic insects with which to compare.

Effect of Irradiation on Fresh Commodities

It goes without saying that any quarantine treatment is worthless if it intolerably damages the commodity to which it is applied. Commodity quality is the other leg of a successful quarantine treatment, and appropriate research on the effects of a treatment to the commodity must be carried out concurrently with efficacy research. In general, any quarantine treatment will cause at the very least a small and negligible amount of damage to fresh fruits and vegetables. Contrary to cursory claims common in the literature, it is rare that a quarantine treatment causes absolutely no detrimental change or, rarer still, enhances the quality of fresh produce. For example, even though immersion of mangoes in hot water reduces certain peel diseases (McGuire 1991), it causes other problems to fruit quality (Smith 1990). Nonetheless, low dose irradiation has been recommended to prolong shelf life and delay ripening of produce and is probably the most broadly applicable quarantine treatment from the standpoint of commodity quality.

An important concern with irradiation quarantine treatments stems from the fact that the treatment will most likely be applied to pallet loads of packed commodities. Therefore, because of distance and attenuation, produce closest to the radiation source will receive up to three times the absorbed dose reaching the farthest produce. Therefore, fresh commodities must tolerate up to three times the absorbed minimum dose required for efficacy. For example, if the minimum absorbed dose to prevent spider mite repro-

Table 3. Estimated doses required to achieve 100% sterility in both sexes of many adult insects and mites

Order and Arthropod	Dose (Gy)[1]		Reference
	Female	Male	
COLEOPTERA: Anobiidae			
Cigarette beetle, *Lasioderma serricorne* (F.)	175	250	Tilton *et al.* (1966b)
Drugstore beetle, *Stegobium paniceum* (L.)	300	>300	
Bostrichidae			
Lesser grain borer, *Rhyzopertha dominica* (F.)	50	50	Singh & Lilies (1972)
Coccinellidae			
Mexican bean beetle, *Epilachna varivestis* Mulsant	80	80	Henneberry *et al.* (1964)
Curculionidae			
Boll weevil, *Anthonomus grandis* Boheman	~70	>80	Earle *et al*. (1978), Haynes *et al*. (1978)
Plum curculio, *Conotrachelus nenuphar* (Herbst)	80	80	Jacklin *et al.* (1970)
White pine weevil, *Pissodes strobi* (Peck)	<200	>200	Jaynes & Godwin (1957)
Sweetpotato weevil, *Cylas formicarius-*	200	300	Dawes *et al.* (1987)
elegantulus (Summers)	300	150	Sharp (1995)
Granary weevil, *Sitophilus granarius* (L.)	<100	>100	Brown *et al.* (1972)
Maize weevil, *S. zeamais* Motschulsky	100	>100	Brown *et al.* (1972)
Dermestidae			
Black carpet beetle, *Attagenus unicolor* (Brahm)	130	175	Tilton *et al*. (1966a)
Trogoderma glabrum (Herbst)	≤175	250	Tilton *et al*. (1966a)
Khapra beetle, *T. granarium* Everts[2]	60	160	Nair & Rahalkar (1963)
T. inclusum LeConte	200	250	Brower & Tilton (1972)
Warehouse beetle, *T. variabile* Ballion	100	250	Brower & Tilton (1972)
Scarabaeidae			
European chafer, *Rhizotrogus majalis* (Razoumowsky)	25	>100	Chung *et al.* (1971)
Japanese beetle, *Popillia japonica* Newman	150	150	Ladd *et al.* (1973)
Tenebrionidae			
Depressed flour beetle, *Palorus subdrepressus* (Wollaston)	400	400	Brower (1973a)
Yellow mealworm, *Tenebrio molitor* L.	50	150	Brower (1973b)
Dark mealworm, *T. obscurus* F.	<100	100	Brower (1973b)
HETEROPTERA: Pyrrhocoridae			
Cotton stainer, *Dysdercus koenigii* F.	20	40	Srivastava & Deshpande (1983)
HOMOPTERA: Aleyrodidae			
Whitefly, *Trialeurodes vaporariorum* Westwood	≤50	60	Calvitti *et al.* (1997)
Cicadellidae			
Beet leafhopper, *Circulifer tenellus* (Baker)[3]	~50	~180	Amereskere & Georghiou (1971)
Delphacidae			
Brown planthopper, *Nilaparvata lugens* (Stål)[3]	≤25	>50	Mochida (1973)
Sugarcane delphacid, *Perkinsiella saccharicida* Kirkaldy[3]	35	100	Osborn *et al*. (1966)
LEPIDOPTERA: Gelechiidae			
Angoumois grain moth, *Sitotroga cerealella* (Olivier)	1,000	>1,000	Cogburn *et al*. (1966)
Pyralidae			
Almond moth, *Cadra cautella* (Walker)	300	>500	Cogburn *et al.* (1973)
Rice moth, *Corcyra cephalonica* (Stainton)	100	>200	Huque (1971)
	—	>350	Chand & Sengal (1979)

Indian meal moth, *Plodia interpunctella* (Hübner)	>1,000	>1,000	Cogburn *et al.* (1966)
Tortricidae			
Rose leafroller, *Clepsis spectrana*	100	150	
Codling moth, *Cydia pomonella* (L.)	200	>500	Hathaway (1966)
ACARI: Acaridae			
Bulb mite, *Rhizoglyphus echinopus* (Fumouze & Robin)	500	600	Ignatowicz (1992)
Tetranychidae			
Oligonychus biharensis (Hirst)	>200	200	Majumder *et al.* (1996)
Citrus red mite, *Panonychus citri* (McGregor)	320	160	Beavers *et al.* (1971)
Twospotted spider mite, *T. urticae* Koch	320	320	Henneberry (1964)
	200	300	Nelson & Stafford (1972)
	300	280	Wakid *et al.* (1972)

[1]Doses are my interpretation of reported results based on estimation of doses required to provide quarantine security.
[2]Pupae irradiated; dose to sterilize adult would probably be higher.
[3]Fifth instar irradiated; dose to sterilize adult would probably be higher.

duction was set at 0.3 kGy, then any produce irradiated for spider mite quarantine would need to be tested for tolerance to up to three times that amount or 0.9 kGy.

Morris & Jessup (1994) review the many effects to the appearance, taste, color, shelf life, texture, chemical content, and pathogens of irradiated produce. Some fruits, such as avocados and atemoyas, are not tolerant of more than low doses, while other, such as papaya, strawberries, pomes, blueberries, cherries, carambolas, and lychees, tolerate >0.6 kGy. The literature of some fruits, such as citrus and mangoes, shows considerable variation in response. As with most quarantine treatments, modifying factors, such as cultivar, maturity, time between harvest and treatment, and post-treatment handling may affect response of the commodity.

Doses to Achieve Quarantine Security

Doses which might achieve quarantine security against several groups of pests are presented in Table 4. Most of these doses need further research because only tephritids have been done with sufficient numbers of insects to satisfy the degree of confidence demanded of quarantine treatments. Many groups of pests from the important orders Diptera, Coleoptera, and Homoptera are controlled with relatively low doses which are tolerated by many plant hosts. Other important groups, such as tetranychid mites and Lepidoptera, are controlled by moderate doses (0.2-0.3 kGy) which, when tripled to allow for commercial application, are tolerated by some major commodities, such as apples, cherries, and blueberries.

Conclusions and Future Directions

Irradiation is a viable quarantine treatment with the potential to disinfest a wide variety of fresh commodities of many quarantined pests. One problem is that irradiation facilities do not widely exist and are expensive to build. However, irradiation facilities have other potential uses, such as parasite and bacterial control in meats and other products, delayed ripening and prolonged shelf life of fresh produce, and sterilization of medical implements. It would be wise to construct facilities at ports or areas which could take advantage of multiple use potential.

Consumer acceptance of irradiated food has not been a problem, although activists opposed to irradiation have been energetic in trying to hinder its use.

Although considerable research on irra-

Table 4. Absorbed dose ranges which might achieve quarantine security of several pest groups.

Pest group	Objective	Dose (KGy)
Bruchid weevils	Sterilize adult	0.07-0.1
Aphids, whiteflies	Sterilize adult	0.05-0.1
Tephritid flies	Prevent adult emergence from third instar	0.05-0.25
Scarab beetles	Sterilize adult	0.05-0.15
Curculionid Weevils	Sterilize adult	0.1-0.2
Noctuidae and Tortricidae	Prevent adult emergence from late instar	0.1-0.3
Pyralidae and Tortricidae	Sterilize late pupa	0.2-0.3
Tetranychid mites	Sterilize adult	~0.3
Stored product beetles	Sterilize adult	0.05-0.4
Acarid mites	Sterilize adult	~0.5
Stored product moths	Sterilize adult	0.1-1
Root-knot nematodes	Sterilize adult	~4

diation as a quarantine treatment has been performed, scant information exists on radiation-susceptibility of important pest groups, such as molluscs, mealybugs and scales (Homoptera: Coccoidea), thrips (Thysanoptera), and eriophyid mites.

Some factors, especially hypoxia, increase tolerance to irradiation (Hallman & Worley 1998). Also, response of some fresh commodities, such as mangoes, to irradiation has been quite variable (Morris & Jessup 1994). Modifying factors must be identified and their effect on the pests and fresh plant products clearly understood so that efficacy in controlling the pests and reduction in damage to commodity quality can be optimized.

The combination of irradiation with other techniques, such as extreme temperatures, should be examined for those commodities and insects which show problems with a single irradiation treatment. Although von Windeguth & Gould (1990) claimed that a combination irradiation (50 Gy)-cold (1.1°C for 5 days) treatment of grapefruits infested with Caribbean fruit fly, *Anastrepha suspensa* (Loew), resulted in a reduction in dose needed for either treatment done alone, it seems that 50 Gy by itself could have achieved the same level of security as the combination treatment, thus, negating the need for the accompanying cold treatment (von Windeguth & Ismail 1987).

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