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# Irradiation for Postharvest Control of Quarantine Insects 【Review article】

# 輻射照射於檢疫害蟲之採後處理【綜合論述】

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## Abstract

Interest in the use of irradiation as a phytosanitary treatment for agricultural commodities is growing worldwide, particularly since publication of the International Plant Protection Convention (IPPC) standard that endorses and facilitates trade based on this disinfestation method. Irradiation is broadly effective against insects and mites at doses that do not compromise quality of most commodities. Unlike other disinfestation techniques, irradiation does not need to kill the pest immediately to provide quarantine security, and therefore live but sterile or not viable insects may occur with the exported commodity making inspection for the target pests redundant. Generic irradiation treatments have been approved in the USA to control broad groups of insects in all commodities. The approved generic doses are 150 Gy for tephritid fruit flies and 400 Gy for all insects except Lepidoptera pupae and adults (which may require higher doses). Generic irradiation treatments will accelerate the approval of irradiation quarantine treatments for specific crops and expedite new trade in agricultural products because research will no longer be needed for each quarantine pest and commodity. The availability of generic treatments makes irradiation an attractive option compared with other quarantine treatments.

## 摘要

輻射照射（irradiation）早已被用為滅除農產品上有害生物的處理方法之一。近年來由於國際植物保護公約（The International Plant Protection Convention, IPPC）制定了使用輻射照射進行檢疫處理（phytosanitary treatment）的國際規範，更促使其逐漸受到各國的重視。一般農產品經由適當的輻射照射劑量，即可在不影響品質的情況下，對多數害蟲（蟎）產生良好的滅除效果（disinfestation effect）。與其他檢疫處理方法相較，輻射照射處理並不以立即殺死害蟲（蟎）的方式來確保檢疫的安全性。因為經過輻射照射處理之農產品，雖然其中的檢疫害蟲（蟎）仍可能存活，但它們已是不孕的或是近乎死亡的，進口國並不需要再耗費精力檢視它們是否存在。目前美國政府更訂定了輻射照射做為各式農產品檢疫處理的共通處理劑量（generic treatment doses），例如滅除各類果實蠅的共通處理劑量為150 Gy，而除鱗翅目的蛹與成蟲（需經較高的劑量處理）以外，其它檢疫害蟲（蟎）的共通處理劑量為400 Gy，並允許多項經此等劑量處理之農產品經過檢疫認證後直接輸入。輻射照射共通處理劑量的訂定，不但可加速特定農產品利用輻射照射處理以符合檢疫要求，同時亦可加速其他新農產品在國際市場的開拓，因為新的農產品僅需依此基準處理過即可通過檢疫認證，不需再耗費冗長的時間，針對不同害蟲（蟎）進行各種不同的檢疫處理試驗，才可能獲得進口國的檢疫認證。因此，相較於其它檢疫處理方法，由於共通處理劑量的確立，使得輻射照射成為一項深具潛力、足以取代其他檢疫處理的替代方法。

**Key words:** irradiation, phytosanitary treatment, quarantine pest, probit 9 alternatives, generic treatments

**關鍵詞:** 輻射照射、植物檢疫處理、檢疫害蟲、probit 9的選擇、共通處理劑量。

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# Irradiation for Postharvest Control of Quarantine Insects

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**ABSTRACT**

Interest in the use of irradiation as a phytosanitary treatment for agricultural commodities is growing worldwide, particularly since publication of the International Plant Protection Convention (IPPC) standard that endorses and facilitates trade based on this disinfestation method. Irradiation is broadly effective against insects and mites at doses that do not compromise quality of most commodities. Unlike other disinfestation techniques, irradiation does not need to kill the pest immediately to provide quarantine security, and therefore live but sterile or not viable insects may occur with the exported commodity making inspection for the target pests redundant. Generic irradiation treatments have been approved in the USA to control broad groups of insects in all commodities. The approved generic doses are 150 Gy for tephritid fruit flies and 400 Gy for all insects except Lepidoptera pupae and adults (which may require higher doses). Generic irradiation treatments will accelerate the approval of irradiation quarantine treatments for specific crops and expedite new trade in agricultural products because research will no longer be needed for each quarantine pest and commodity. The availability of generic treatments makes irradiation an attractive option compared with other quarantine treatments.

**Key words:** irradiation, phytosanitary treatment, quarantine pest, probit 9 alternatives, generic treatments

## Introduction

World trade in agricultural commodities continues to grow. As agricultural trade is increasing, the risk of introducing exotic insects into new areas where they may become plant pests will increase. The establishment of new pests can be costly due to increased crop damage, control programmes, and quarantine restrictions on trade. Quarantine treatments or systems eliminate, sterilize, or kill

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regulatory pests in exported commodities to prevent their introduction and establishment into new areas. As exclusion is the goal for quarantine pests, the tolerance for the pest in the commodity is essentially zero (Follett and Neven, 2006). Quarantine or phytosanitary treatments such as heat, cold, irradiation, and fumigation disinfest host commodities of insect pests before they are exported to areas where the pests do not occur. Whereas development of heat, cold, and fumigation treatments involves generating data for each commodity and pest combination, irradiation treatments are developed for a pest species irrespective of the fruit or vegetable host. This is possible because ionizing radiation penetrates commodities quickly without changing the commodity's temperature, and most commodities can tolerate irradiation at doses that control the pest (Morris and Jessup, 1994, Thomas, 2001). Developing heat, cold and fumigation treatments, on the other hand, involves finding a balance between killing the pest and minimizing the adverse effects of the treatment process on commodity quality (Paull, 1994).

Unlike other disinfestation techniques, irradiation does not need to kill the pest immediately to provide quarantine security, and therefore live (but sterile or not viable) insects may occur with the exported commodity making inspection for the target pests redundant as a confirmation of treatment application and efficacy. This places an added level of importance on the certification procedures for irradiation facilities and proper documentation accompanying export shipments confirming treatment at approved doses. It also places an added responsibility on researchers to ensure that the minimum absorbed dose approved for each quarantine pest has an adequate margin of safety. Irradiation technology is not universally accepted as a phytosanitary treatment (Follett and Neven, 2006). For example, Japan, Taiwan, and the European Union have not approved the use of irradiation as a phytosanitary treatment. However, irradiation as a phytosanitary measure is now approved internationally by the International Plant Protection Convention (FAO, 2003), and may provide an alternative for replacing current treatment methods. Herein, several recent developments in the application of irradiation and risk management are discussed that should expand the use of the technology worldwide and facilitate trade in agricultural commodities, particularly fresh commodities.

**Radio-tolerance of insects**

Arthropod groups vary in their tolerance to irradiation (Table 1). Among insects, Diptera (flies), Coleoptera (beetles), Hemiptera (true bugs) tend to be less radiotolerant than Lepidoptera (moths and butterflies), although there is considerable variation among the species that have been tested within these groups (Hallman, 2000, Bakri *et al.*, 2005). Estimates for Hemiptera (scales, mealybugs, aphids and whiteflies) and Thysanoptera (thrips) are based on a small number of studies. Two of the most radiotolerant insects are the Indian meal moth, *Plodia interpunctella*, and the Angoumois grain moth, *Sitrotroga cerealella*, both stored products pests (Ahmed, 2001, Ignatowicz, 2004). The Angoumois grain moth reproduced at 500 but not 600 Gy (Ignatowicz, 2004). Most insects are controlled at doses below 300 Gy. Several species of mites have been tested and they appear to be relatively tolerant of ionizing radiation. Theoretically, the high dose in the range for each pest group in Table 1 could be used as a generic dose. However, the dose ranges are often estimates from limited data or from a limited sample of species within the group. Few studies have conducted the large-scale validation tests needed to confirm the efficacy of an irradiation dose

Table 1. Range of doses predicted to control various arthropod pest groups

| Pest Group | Desired Response | Dose Range (Gy) |
|---|---|---|
| Hemiptera | Sterilize adult or prevent generation turnover | 50-250 |
| Thrips | Sterilize actively reproducing adult | 150-350 |
| Tephritid fruit flies | Prevent adult emergence from eggs/larva | 50-150 |
| Bruchid seed weevils | Sterilize actively reproducing adult | 70-300 |
| Curculionid weevils | Sterilize actively reproducing adult | 80-150 |
| Scarab beetles | Sterilize actively reproducing adult | 50-150 |
| Stored product beetles | Sterilize actively reproducing adult | 50-250 |
| Stored product moths | Sterilize actively reproducing adult | 100-600 |
| Lepidopteran borers | Prevent adult emergence from eggs/larva | 100-250 |
| | Sterilize adult from late pupa | 200-400 |
| Mites | Sterilize actively reproducing adult | 200-400 |

Modified from FAO (2003)

predicted to give 100% mortality (discussed below).

### Methodology for developing irradiation quarantine treatments

The goal of irradiation as a phytosanitary treatment is to provide quarantine security for any regulated pests residing in or on the exported commodity. This is most often accomplished by preventing development to the reproductive stage or sterilizing the reproductive stage of the insect.

If multiple species on a commodity are regulated pests, irradiation studies begin by comparing the tolerance of the quarantine pests, then, in-depth studies focus on the most tolerant stage of the most tolerant species, to arrive at a single dose providing quarantine security for the commodity. Typically the most advanced developmental stage of the insect occurring in the commodity is the most tolerant when the goal is preventing adult emergence or reproduction. The most advanced stage may be the larva (or nymph), pupa, or adult. When larval development is completed in the host but the insect pupates outside the host, irradiation is applied to prevent adult emergence. In the case of tephritid fruit flies, preventing adult emergence is the desired response required for regulatory purposes because it prevents the emergence of adult flies that could be trapped and trigger regulatory actions, despite being sterile. When the insect pupates in the host, preventing adult emergence may be difficult so adult sterility is the goal.

Often adults occur with the commodity (e.g. Follett, 2006a). When the adult stage can occur in the commodity and is the most tolerant stage, the measure of treatment efficacy is the level of sterility. For sexually reproducing species, sterilizing one sex may be sufficient to prevent reproduction but both sexes must be sterilized if mating status is unknown as is usually the case. Males are often but not always more tolerant than females. Reciprocal crosses between irradiated and control males and females at several sub-sterilizing doses are useful to determine the more tolerant sex (Follett and Lower, 2000). In large-scale validation tests, males and females should be mated before treatment and females should have begun ovipositing. After irradiation treatment, surviving males and females are combined and allowed to mate and reproduce to determine the success of the dose. Adult females irradiated at a sterilizing dose will often oviposit (particularly if they were gravid when irradiated) but eggs will not hatch or hatching neonates do not develop. With asexual species the female is the focus of all tests. In rare cases irradiated insects will recover so it is important to continue tests until all insects have died.

Many insect species have life history attributes that complicate testing methods. For example, diaspidid scale insects are sessile (attached to the plant) and long-lived, and so experiments must use host material (e.g. pumpkin) that does not deteriorate after irradiation treatment and before the insects die. Some species require live host material to survive. The long-lived semi-sessile coccid scale, green scale (*Coccus viridis*) only survives on live host material such as gardenia, coffee and hibiscus, which complicates testing since irradiation treatment causes rapid plant deterioration (Hara *et al.*, 2002). Diapausing and non-diapausing strains of insects may have different tolerances to radiation, and may require different bioassay methods (Hallman, 2003).

To determine the most tolerant stage for a species, all stages are treated with a range of irradiation doses. Generally five doses should be selected and five replicates of at least 30-50 insects should be used. In some cases a single diagnostic dose is used to separate tolerance among stages or species. The ideal diagnostic dose causes only moderate mortality in the stage or species predicted to be most tolerant. This improves the chances that statistical tests can be used to separate mean responses among groups. Tests should be designed with the biology of the insect in mind, and insects should always be tested in the commodity of interest if possible. For example, pupae may be inherently more tolerant of irradiation than larvae but because they only occur at the surface of the fruit they may be easier to sterilize than larvae that feed at the center of the fruit where hypoxic conditions exist (low oxygen can increase radio-tolerance) (Follett and Armstrong, 2004, Hallman, 2004). If artificial inoculation is used, insects should be placed where they occur naturally or allowed time to redistribute to preferred feeding sites in the commodity. Dosimeters should be placed where the insects occur to accurately measure absorbed doses.

Once dose response tests are completed, large-scale tests are conducted with the most tolerant life stage at a dose predicted to cause 100% mortality. The dose determined to provide quarantine security from testing large numbers of insects is often higher than that predicted from small-scale dose response tests to give 100% mortality. Insects are irradiated in the commodity after inoculation with a known number of insects or in naturally infested host material. For internal feeding insects naturally infesting the commodity, the number of viable insects treated is estimated by the number of insects successfully emerging in paired samples of untreated controls. Untreated control insects are always included in tests with irradiated insects so that mortality can be adjusted for natural variation and to guard against changes in experimental conditions over the course of testing that cause higher than normal mortality. While control mortality $\leq$ 20% is desirable, higher mortality may be normal when using wild insects and naturally infested commodities.

Probit analysis is the standard method to evaluate dose response data, but other models (e.g. logit) should be used if they provide a better fit to the data (Robertson *et al.*, 1994). These analyses are used to compare radiotolerance among life stages or species, and to help identify a target dose for large-scale testing. Covariance analysis is an alternative to compare response among stages or between species. Covariance analysis requires the slopes of the regression lines fitted to each group to be parallel, so the test of parallelism (nonsignificant stage or species by dose interaction effect) is tested before comparing stage or species effects (e.g. Follett and Armstrong, 2004).

As mentioned, the actual dose to achieve quarantine security at a given level of precision may exceed the dose predicted from small-scale dose response tests. For example, the dose predicted to prevent emergence of adult melon flies treated in papaya from dose response data was 90 Gy (0 survivors in 900 tested insects) (Follett and Armstrong, 2004); however, subsequent large-scale testing at 120 Gy resulted in 1 survivor out of 50,000 treated third instars and several partially emerged pupae. Increasing the dose for large-scale testing to 150 Gy resulted in 0 survivors in 96,700 treated insects and no partial pupal emergence (Follett and Armstrong, 2004). This demonstrates the need for large-scale testing to verify a dose.

Accurate dosimetry is critical to the success of insect irradiation studies. The objective in research is to minimize the dose uniformity ratio (DUR) (also called the maximum:minimum ratio), thus reducing variation in dose response tests. This allows the researcher to more accurately pinpoint an efficacious dose without excessive overkill. The maximum dose measured during large-scale testing becomes the minimum dose for a treatment (Heather, 2004). Dose rate decreases with the square of the distance from the source (e.g. if distance from source is doubled, dose rate decreases by a factor of 4). Small scale research irradiators such as the Gammacell 220 types (MDS Nordion, Canada) have a small radiation chamber volume and hence all locations in the product during irradiation are a short distance from the source and DURs can be minimized (typically $<$ 1.2:1). It is generally accepted that large-scale commercial irradiators are not useful for conducting dose response research because of high DURs, sometimes in the range of 3:1. High DURs are the result of product volume and density, not the size of the irradiator. When using commercial irradiators for research applications, DURs can be minimized by presenting product of minimal depth (e.g. individual fruits) and irradiating the product in a forward then reverse orientation. For example, Follett and Armstrong (2004) irradiated fruit fly larvae in papayas at a commercial x-ray facility using an electron linear accelerator (5 MeV, model TB-5/15, SureBeam Corp., San Diego, California). To minimize the DUR, infested fruit were placed upright in plastic tubs in a single row perpendicular to the beam. Dose mapping demonstrated that doses were sometimes lower near the sides and floor of the metal carrier, so the tubs with fruit were elevated by placement on a cardboard box and positioned in the exact center of the carrier. Each carrier passes in front of the beam in a forward then reverse orientation. DURs in this study were consistently $<$ 1.2 (Follett and Armstrong, 2004).

**Probit 9 treatments**

The question always arises: How many insects must be tested during research to demonstrate that a treatment provides quarantine security? Future trade between countries in a commodity that is potentially infested by a quarantine pest can be slowed by the lack of a standardized research protocol for developing a quarantine treatment or system. The exporting country must often initiate research on a crop or quarantine pest without full knowledge of the commitment of time and resources involved because the importing country has not published or explicitly outlined a research protocol. Hence the number of insects to treat in validation tests and other research requirements can vary dramatically depending on the pest, the crop, and the country.

In the U.S., post-harvest commodity

treatments for pests requiring a high degree of quarantine security are commonly referred to as probit 9 treatments. The reference originates from the statistical method (probit analysis) used for deriving the dose-response relationship. A response at the probit 9 level results in 99.9968% efficacy. The required response may be mortality, sterility, or prevention of maturity. The United States Department of Agriculture (USDA) has used 99.9968% efficacy as the basis for approving many quarantine treatments, particularly for tephritid fruit flies. A probit 9 treatment usually provides adequate quarantine security, and developing the treatment frequently proves to be the quickest and most easily accepted method for overcoming phytosanitary restrictions (Follett and Neven, 2006).

To achieve probit 9 mortality at the 95% confidence level, a minimum of 93,613 insects must be tested with no survivors after exposure to the treatment. Quantitative methods have been developed to calculate the number of test insects and confidence limits for other levels of precision and treatment efficacy, with and without survivors (Couey and Chew, 1986). Although probit 9 testing seems like a comfortable level of safety, given a highly-infested commodity or a high enough volume of infested commodity imports, even probit 9 security could be overwhelmed (Mangan *et al*., 1997, Powell, 2003). Other countries (Japan, Australia, New Zealand) accept quarantine treatment efficacy at 99.99% (at the 95% confidence level), which is obtained by treating 29,956 insects with no survivors (Couey and Chew, 1986). Japan requires a total of 30,000 individuals in 3-4 trials (Sproul, 1976), New Zealand requires three replicates of 10,000 test insects, and Australia accepts a cumulative total of 30,000 treated insects with no survivors (Heather and Corcoran, 1992).

**Alternative approaches**

In certain cases, less-than-probit 9 numbers of insects may be acceptable during quarantine treatment development if the potential economic and environmental impact of the pest should it be introduced is low. For example, irradiation treatment with a dose of 300 Gy was accepted for the mango seed weevil, *Sternochetus mangiferae* (F.) by Animal and Plant Health Inspection Service, USDA (USDA-APHIS, 2002), a monophagous pest of mangos, based on evidence for the weevil's limited potential impact on U.S. agriculture (Follett and Gabbard, 2000), and cumulative data from several studies with a few thousand insects showing prevention of adult emergence from the fruit at this dose and sterilization at lower doses (Seo *et al*., 1974, Heather and Corcoran, 1992, Follett, 2001).

Irradiation negatively affects commodity quality in some cases. Lowering the irradiation dose may reduce the undesirable effects on the commodity. Landolt *et al*. (1984) pointed out that the probit 9 standard may be too stringent for commodities that are rarely infested or are poor hosts, and hence a less severe post-harvest treatment might still provide quarantine security. The less-than-probit 9 or alternative treatment efficacy approach measures risk as the probability of a mating pair or reproductive individual surviving in a shipment. This will be a function of many biological, operational, and environmental factors (Vail *et al*., 1993, Yamamura and Katsumata, 1999, Follett and Neven, 2006). The main quantitative argument for deviating from probit 9 treatment efficacy is low infestation rate of the commodity, resulting from poor host status, early harvesting, or effective pre-harvest pest suppression.

A number of quarantine pest-commodity systems are amenable to the less-than-probit 9 approach (Liquido *et al*., 1995, Follett and McQuate, 2001). For example, nectarines are an inherently poor host for codling moth, *Cydia pomonella* (L.). Only three live codling moths (larvae) were found infesting 326,625 packed nectarines sampled from packinghouses in the San Joaquin Valley of California for an infestation rate of 9.2 x $10^{-6}$ (Curtis *et al.*, 1991). In an average shipment of 16,000 kg (89,600 fruits), the probability of one or more mating pairs surviving after a probit 9-level quarantine treatment is 1.7 x $10^{-10}$. The actual mortality level required from a quarantine treatment to prevent a mating pair of codling moths in a single shipment of nectarines with 95% confidence is 77.74% (probit 5.65). Hypothetically, if 100 shipments arrived at the same location the probability of one or more codling moth mating pairs surviving in nectarines after a probit 9-level quarantine treatment is still extremely small (1.7 x $10^{-6}$). In this case, a probit-9 treatment provides a high level of overkill and a less severe treatment might be developed that provides adequate quarantine security while minimizing any negative effects of the treatment on commodity quality. Low infestation rate at harvest can also be the result of effective pest management before harvest and/or the harvest of climacteric fruit (those that continue to ripen after harvest) at a less susceptible or non-preferred maturity stage. An additional advantage to use of the less-than-probit 9 approach is that fewer insects may be needed during research to develop quarantine treatments, which would make new treatments available on a more timely basis (Follett and McQuate, 2001).

The less-than-probit 9 approach fits with the systems approach where multiple procedures are used to cumulatively provide quarantine security while maintaining quality in a commodity that is sensitive to a particular quarantine treatment (Jang and Moffitt, 1994). For example, a less-than-probit 9 irradiation dose for a fruit fly might be part of a systems approach that included effective pest suppression in the crop, poor host status, fruit cutting and inspection, limited distribution period (winter months), and limited geographic area for distribution (i.e. to non-fruit fly supporting areas).

**Generic irradiation doses**

A generic treatment, a single treatment that controls a broad group of pests without affecting the quality of a wide range of commodities, is the ultimate discovery sought after by quarantine entomologists, albeit seldom found. Most quarantine treatments are developed for one pest and one commodity at a time, and research may take several years. Generic treatments for broad groups of pests and commodities accelerate the research, shorten treatment development, and save resources. Irradiation is the ideal technology for developing generic treatments because radiation– from an isotope source such as cobalt-60, or x-rays– penetrates fruit easily and is effective against insects at doses that generally do not injure the commodity.

A generic treatment for a group of insects could be applied at many taxonomic levels, e.g. to all Diptera (flies), or to flies in the family Tephritidae (fruit flies), or to tephritid fruit flies in the genus *Bactrocera*. A generic irradiation dose is recommended after information has accumulated on effective quarantine irradiation doses for a wide range of insects within the taxon or for the important economic pests within the taxon (Follett and Neven, 2006, Bakri and Hendrichs, 2004). The rationale is that related species are likely to be similar in their radio-tolerance, and therefore data for a limited number of species can be extrapolated to other related species to arrive at a generic dose.

Recently, generic irradiation treatments were approved for the first time. On January 27, 2006, USDA-APHIS approved generic doses of 150 Gy for tephritid fruit flies and 400 Gy for all insects except pupa and adult Lepidoptera (USDA-APHIS, 2006). The rule also included lower doses for a number of well-studied

Table 2. Irradiation doses approved for insects and insect groups by the USDA

| Scientific Name | Common name | Dose (Gy) |
|---|---|---|
| *Anastrepha ludens* | Mexican fruit fly | 70 |
| *Anastrepha obliqua* | West Indian fruit fly | 70 |
| *Anastrepha serpentina* | Sapote fruit fly | 100 |
| *Anastrepha suspensa* | Caribbean fruit fly | 70 |
| *Bactrocera jarvisi* | (none) | 100 |
| *Bactrocera tryoni* | Queensland fruit fly | 100 |
| *Brevipalpus chilensis* | False red spider mite | 300 |
| *Conotrachelus nenuphar* | Plum curculio | 92 |
| *Cryptophlebia ombrodelta* | Litchi fruit moth | 250 |
| *Cryptophlebia illepida* | Koa seedworm | 250 |
| *Cylas formicarius elegantulus* | Sweetpotato weevil | 150 |
| *Cydia pomonella* | Codling moth | 200 |
| *Euscepes postfasciatus* | West Indian sweetpotato weevil | 150 |
| *Grapholita molesta* | Oriental fruit moth | 200 |
| *Omphisa anastomosalis* | Sweetpotato vine borer | 150 |
| *Rhagoletis pomonella* | Apple maggot | 60 |
| *Sternochetus mangiferae* | Mango seed weevil | 300 |
| Fruit flies in the family Tephritidae not listed above | | 150 |
| Plant pests of the Insecta not listed above, except Lepidoptera pupae and adults | | 400 |

Source: Federal Register 2006

quarantine insect species (Table 2). The generic and specific irradiation doses apply to all agricultural commodities. The generic dose for tephritid fruit flies of 150 Gy was based on data for 17 species of *Anastrepha*, *Bactrocera*, *Ceratitis*, and *Rhagoletis* fruit flies (Hallman and Loaharanu, 2002, Follett and Armstrong, 2004). The default dose of 400 Gy for all insects except pupae and adults of Lepidoptera was recommended after critical analysis of the literature (Follett and Hallman unpublished report). The default dose was first used for sweet potatoes exported from Hawaii to the U.S. mainland. With the default dose approach, an irradiation dose is set at the upper limit of what is believed to control the insect groups that infest a commodity without specific data for the quarantine species. A default dose of 400 Gy was used for Hawaii sweet potato (USDA-APHIS, 2004) until research later demonstrated that 150 Gy was sufficient (Follett, 2006a). New Zealand prepared a rule to allow import of tropical fruits from Australia using generic irradiation treatments of 150 Gy for fruit flies, 250 Gy for other insects, and 300 Gy for mites (Corcoran and Waddell, 2003). Any country negotiating trade in a fresh fruits and vegetables with the U.S. can use the generic irradiation treatments, and adoption of these or other generic irradiation doses for tephritid fruit flies and other insect groups by other countries is anticipated.

The generic irradiation doses can be lowered for specific pests and commodities if this is practical. For example, papayas exported from Hawaii to the U.S. mainland are routinely irradiated at a minimum dose of 400 Gy to control white peach scale (*Pseudaulacaspis pentagona*) in addition to fruit flies because no information was available the radiotolerance of this scale. Recent studies demonstrated that white peach scale is controlled at 150 Gy (Follett, 2006b). Hence, an irradiation treatment with a minimum absorbed dose of 150 Gy should provide quarantine security for white peach scale in addition to fruit flies on exported papaya. Lowering the dose will significantly reduce costs of treatment and increase capacity of the treatment facility.

Theoretically, a universal irradiation dose could be set for all insects. The most radio-tolerant insect species reported to date is the Angoumois grain moth, a stored product pest which successfully reproduced after irradiation treatment at a dose of 500 Gy but not at 600 Gy (Ignatowicz, 2004). If this is indeed the most tolerant insect, irradiation treatment with a minimum absorbed dose of 600 Gy should control any insect. A limiting factor for the practical use of a generic treatment at 600 Gy in the U.S. is the 1000 Gy (1 kGy) maximum allowed dose for fresh produce set by the Food and Drug Administration. With typical dose uniformity ratios at commercial irradiation facilities of 1.5-3.0, treatment to achieve a minimum absorbed dose of 600 Gy without exceeding 1 kGy would be difficult. Also, doses above 600 Gy adversely affect the quality of many fresh commodities (Morris and Jessup, 1994). Another approach would be to set the generic dose for insects at a dose lower than 600 Gy and exclude any species or insect groups found to tolerate a dose above this level (Follett and Armstrong, 2004, Follett and Griffin, 2006).

**Case study: Longan from Taiwan to the U.S.**

One of the earliest published studies examining the use of irradiation as a quarantine treatment was by Koidsumi (1930) in Taiwan (Formosa). He systematically tested the lethal effects of various dosages of X-ray to oriental fruit fly, *Bactrocera dorsalis*, and melon fly, *B. curcubitae*, at different developmental stages. Irradiation continues to be a topic of interest in Taiwan, with several studies published recently on pests of stored products, such as the cigarette beetle, *Lasioderma serricorne* (Hu *et al.*, 2002a), rice weevil, *Sitophilus oryzae* (Hu *et al.*, 2002b), maize weevil, *S. zeamais* (Hu *et al.*, 2003), and the carambola fruit borer, *Eucosma notanthes* (Lin *et al.*, 2003).

The United States and Taiwan are negotiating trade in Taiwan longan. The first step in the process is the preparation of a pest risk assessment. This document is a listing of all the insect, disease and weed species associated with the commodity, and a risk rating for each pest. This list is used to develop risk mitigation or control options for the pests so that the commodity can be exported. The tentative list of high- and medium-risk pests that might occur in exported Taiwan longan is presented in Table 3 (USDA-APHIS personal communication). This is a relatively long list, consisting of 5 high risk pests and 21 medium risk pests. By comparison, the pest risk assessment for Hawaii's longan exported to the U.S had 4 high risk pests (*B. dorsalis*, *B. cucurbitae*, and *Ceratitis capitata*, and *M. hisutus*) and 3 medium risk pests (including *Cryptophlebia ombrodelta*). Typically, high-risk pests require a proven mitigation procedure such as a quarantine treatment, whereas medium-risk pests may not require a quarantine treatment per se provided infestations can be identified during inspection.

The simplest and quickest risk mitigation option for Taiwan longan is irradiation at a dose of 400 Gy. The generic treatment rule provides a treatment of 400 Gy to control all insects except Lepidoptera (moths and butterflies) pupae and adults. If none of the Lepidoptera associated with Taiwan's longan are associated with the fruit as pupae or adults, 400 Gy is a ready-made treatment. Research has shown that longan is tolerant of irradiation at 400 Gy, and irradiation is superior to an

Table 3. High- and medium-risk pests identified in a draft USDA-APHIS pest risk assessment for longan imported from Taiwan

| Species | USDA-Approved Dose | Suggested Dose | Reference |
|---|---|---|---|
| **High risk** | | | |
| Diptera | | | |
| *Bactrocera cucurbitae* | 150 | 150 | Follett and Armstrong 2004 |
| *Bactrocera dorsalis* | 150 | 150 | Follett and Armstrong 2004 |
| Lepidoptera | | | |
| *Conogethes punctiferalis* | -- | -- | |
| *Cryptophlebia ombrodelta* | 250 | 250 | Follett and Lower 2000 |
| Thysanoptera | | | |
| *Rhipiphorothrips cruentatus* | -- | -- | |
| **Medium risk** | | | |
| Hemiptera | | | |
| *Ceroplastes rubens* | 400 | -- | |
| *Coccus discrepans* | 400 | -- | |
| *Coccus formicarii* | 400 | -- | |
| *Coccus viridis* | 400 | 250 | Hara *et al.* 2002 |
| *Drepanococcus chiton* | 400 | -- | |
| *Pulvinaria taiwana* | 400 | -- | |
| *Aulcaspis tubercularis* | 400 | -- | |
| *Fiorinia pinicola* | 400 | -- | |
| *Pseudaonidia trilobitiformis* | 400 | -- | |
| *Thyssanofiorinia nephelii* | 400 | -- | |
| *Kerria greeni* | 400 | -- | |
| *Kerria lacca* | 400 | -- | |
| *Icerya seychellarum* | 400 | -- | |
| *Maconellicoccus hirsutus* | 400 | 250 | Jacobson and Hara 2003 |
| *Nipaecoccus viridis hirsutus* | 400 | -- | |
| *Planococcus lilacinus* | 400 | -- | |
| *Planococcus minor* | 400 | -- | |
| Lepidoptera | | | |
| *Conopomorpha litchiella* | 400 | 250 | Hu *et al.* 1999 |
| *Deudorix epijarbas* | 400 | -- | |
| *Dichocrocis punctiferalis* | 400 | -- | |
| *Adoxophyes orana* | 400 | -- | |

Source: USDA APHIS Pest Epidemiological Risk Analysis Laboratory, Raleigh, North Carolina

alternative treatment, hot water immersion (Follett and Sanxter, 2002).

It may be possible to reduce the irradiation dose from 400 Gy if research can show a lower dose is sufficient to control the high-risk pests. For longan, approved doses for the two tephritid fruit flies and *Cryptophlebia ombrodelta* are 150 and 250 Gy, respectively, but there are no approved irradiation doses for *Conogethes punctiferalis* (yellow peach moth) or *Rhipiphorothrips cruentatus* (Table 3). Research should be initiated to identify effective irradiation doses for these quarantine pests. The dose for an irradiation treatment for longan would be the dose that controls the most tolerant high-risk species. Irradiation studies have been conducted on only a few of the medium-risk pests on the list.

## Conclusions

The availability of generic dose treatments makes irradiation an attractive option compared with other quarantine treatments. Developing irradiation treatments for taxonomic groups or guilds of insects and groups of commodities rather than for individual pests and commodities helps avoid unnecessary research, and regulatory and trade bottlenecks. An International Database of Insect Disinfestation and Sterilization (IDIDAS, 2005; Bakri *et al.*, 2005) developed by the International Atomic Energy Agency and the Food and Agriculture Organization of the United Nations contains radiotolerance information for many Coleoptera (79 species, mainly curculionids), Lepidoptera (72 species, mainly pyralids and tortricids), and other pest groups. Information could be gleaned from the database to set additional generic doses although the majority of the studies referenced in the database for individual species were not designed for quarantine purposes and lack the large-scale tests needed to confirm the efficacy of an irradiation dose. Data for other important regulatory arthropod groups such as Thysanoptera, Hemiptera, and Acari are limited. Before generic treatments below 400 Gy can be recommended for a wider range of insect groups, information from coordinated research projects and large-scale tests is needed on effective irradiation doses for key pests and under-represented taxa. Generic irradiation treatments will accelerate the approval of irradiation quarantine treatments for specific crops and expedite new trade in agricultural products.

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# 輻射照射於檢疫害蟲之採後處理

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## 摘　　要

輻射照射（irradiation）早已被用為減除農產品上有害生物的處理方法之一。近年來由於國際植物保護公約（The International Plant Protection Convention, IPPC）制定了使用輻射照射進行檢疫處理（phytosanitary treatment）的國際規範，更促使其逐漸受到各國的重視。一般農產品經由適當的輻射照射劑量，即可在不影響品質的情況下，對多數害蟲（蟎）產生良好的減除效果（disinfestation effect）。與其他檢疫處理方法相較，輻射照射處理並不以立即殺死害蟲（蟎）的方式來確保檢疫的安全性。因為經過輻射照射處理之農產品，雖然其中的檢疫害蟲（蟎）仍可能存活，但它們已是不孕的或是近乎死亡的，進口國並不需要再耗費精力檢視它們是否存在。目前美國政府更訂定了輻射照射做為各式農產品檢疫處理的共通處理劑量（generic treatment doses），例如減除各類果實蠅的共通處理劑量為 150 Gy，而除鱗翅目的蛹與成蟲（需經較高的劑量處理）以外，其它檢疫害蟲（蟎）的共通處理劑量為 400 Gy，並允許多項經此等劑量處理之農產品經過檢疫認證後直接輸入。輻射照射共通處理劑量的訂定，不但可加速特定農產品利用輻射照射處理以符合檢疫要求，同時亦可加速其他新農產品在國際市場的開拓，因為新的農產品僅需依此基準處理過即可通過檢疫認證，不需再耗費冗長的時間，針對不同害蟲（蟎）進行各種不同的檢疫處理試驗，才可能獲得進口國的檢疫認證。因此，相較於其它檢疫處理方法，由於共通處理劑量的確立，使得輻射照射成為一項深具潛力、足以取代其他檢疫處理的替代方法。

**關鍵詞**：輻射照射、植物檢疫處理、檢疫害蟲、probit 9 的選擇、共通處理劑量。

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