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Building lab-scale x-ray tube based irradiators

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HIGHLIGHTS

- X-ray is demonstrated as an alternative to gamma for lab-based irradiation.
- Cabinets using one, two, and four 1000 W tubes are reported.
- Dose rate of 9.8 Gy/min/tube at the center of a 12.7 cm container of instant rice.
- Dose uniformity varies dramatically as the distance from source to container.

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ABSTRACT

Here we report the use of x-ray tube based irradiators as alternatives to gamma sources for laboratory scale irradiation. Irradiators were designed with sample placement in closest possible proximity to the source, allowing high dose rates for small samples. Designs using 1000 W x-ray tubes in single tube, double tube, and four tube configurations are described, as well as various cabinet construction techniques. Relatively high dose rates were achieved for small samples, demonstrating feasibility for laboratory based irradiators for research purposes. Dose rates of 9.76, 5.45, and 1.7 Gy/min/tube were measured at the center of a 12.7 cm container of instant rice at 100 keV, 70 keV, and 40 keV, respectively. Dose uniformity varies dramatically as the distance from source to container. For 2.54 cm diameter sample containers containing adult Navel Orangeworm, dose rates of 50–60 Gy/min were measured in the four tube system.

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1. Introduction

Irradiation of biological materials has long been a critical tool for agriculture in general and agricultural research in particular. In fact, the importance of this tool goes far beyond agriculture and includes fields such as medicine and pharmaceuticals as well. Whatever the need for irradiating materials, recent events and the changing world situation have increasingly made obtaining and maintaining isotopic radiation sources more difficult and expensive. There are a number of reasons for this, including government regulation and restriction in light of Homeland Security concerns, radioisotope suppliers going out of business, and the general aging and weakening of existing sources in radiation facilities. All of these issues regarding the availability of radioisotopes have made their use at the laboratory level for basic research more and more problematic. Alternative to gamma sources are urgently needed. X-ray is an obvious candidate, and in fact x-ray preceded gamma for most irradiation purposes.

There are currently a wide variety of x-ray based irradiation units that are commercially available. Most of these are designed as biological irradiators consisting of a shielded x-ray source mounted adjacent to a sample chamber. Such technology has long been available both for irradiation of samples and for x-ray imaging purposes. More recently, the difficulties in obtaining and maintaining radioisotope sources for Sterile Insect Technique (SIT) programs worldwide has motivated the development of new types of x-ray sources that can deliver higher doses with greater dose uniformity than what can be achieved using traditional x-ray tubes. In 2009 an x-ray tube design was patented that generated

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x-rays along a line rather that the traditional point source, allowing much higher total doses (Kirk, 2009). Also included in this patent was a carousel wheel structure that carried the samples through the x-ray field in such a manner as to maximize dose uniformity through the sample containers. This invention became the basis for the RS 2400 x-ray sterilization system (Rad Source Technologies Inc., Suwanee, GA) and its efficacy to replace gamma irradiation for a variety of applications has been reported. Wagner et al. (2009) tested the various operating parameters of the instrument, reporting dose rates as high as 65 Gy min^{-1} at the tube surface, 37 Gy min^{-1} at the center of the sample canisters, and 14.1 and 12.3 Gy min^{-1} for thin and thick shelled oysters respectively. X-ray beam uniformity within 10% was reported over most of the length of the tube. Mastrangelo et al. (2010) used the RS2400 to demonstrate the sterilization of *C. capitata* and *A. fraterculus* pupae and showed that x-ray irradiation was equivalent to gamma irradiation for insect sterilization. Mehta and Parker (2011) evaluated the system and concluded that it was a suitable replacement to gamma sources for large SIT programs. They reported a dose rate at the center of rice filled canisters of 14 Gy min^{-1} and a dose uniformity across the canister of about 1.3. While many commercially available units advertise a higher dose rate, the unique nature of the carousel system and the 4π tube configuration of the RS2400 allow for a high throughput with highly uniform dose, thus making it a good candidate for large SIT programs. Initial evaluation in the field apparently ran in to some difficulties (IAEA, 2008), but most of the bugs seem to have been worked out within a year (IAEA, 2009). In addition to the 4π tube configuration, manufacturers are introducing x-ray emitter equipment with rectangular transmission windows that dramatically increase delivered dose as compared to conventional tubes. For instance, the XBA-180 x-ray emitter from Comet AG (Flamatt, Switzerland) has a 270×40 mm^2 transmission window. Relatively small scale (as compared to current e-beam facilities) cabinet style x-ray units using these new technologies could provide large growers and packing houses with in-house treatment capability for food phytosanitation purposes as they require limited shielding, would be affordable, and would provide maximum logistical flexibility for quarantine treatment of exported fresh produce. The configuration for such a system has been proposed (Follett, 2014) as shown in Fig. 1.

Even for large SIT programs, the cost of commercially available x-ray units is problematic (IAEA, 2009). At the laboratory level, the cost of obtaining such units for basic research becomes prohibitive in most cases. For such research, throughput is generally not a critical element, and irradiators based on traditional x-ray tubes can be constructed at relatively low cost. Here we report the development of irradiation systems, using one, two, or four tubes arranged in a manner that allows sample placement in immediate proximity to the source, allowing high dose rates for relatively small sample containers.

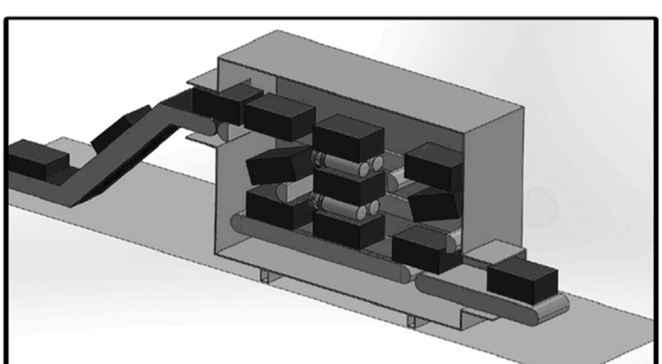

Fig. 1. Cabinet-style irradiator. Schematic design for a proposed conveyor fed cabinet-style x-ray food irradiator for in-line treatment of fresh produce using 4-Pi x-ray tubes (Follett, 2014). The path followed by the food containers maximizes the dose uniformity.

2. Experimental

2.1. X-ray generation

The Comet CXR-105 tube was used as the x-ray source, with a maximum output of 100 keV, and 10 mA (1000 W). Note that Comet now has MXR-100, an x-ray tube that is both 40% lighter (2.1 kg vs 3.5 kg) and 30% smaller as compared to the CRX-105 but with the same power capabilities. The MXR series has a much smaller and more flexible cable between the power supply and the tube which eases implementation. Each tube was powered by a 1000 W power supply (Matsusada Precision Inc., model Xpg-100-N10). The power supply powers the tube through a U3, 5M, HDT 100 KVDC cable (Comet Inc, part number 10001387) with an R10 connector at the power supply end and an R24 connector at the tube end. The tube heads are water cooled using a portable chiller (Advantage Engineering, model # M1-1.5A-21HFX).

2.2. Shielded cabinets

For the four tube design (Fig. 2), a shielded cabinet was acquired from a commercial supplier but required significant modification due to x-ray leakage. Fig. 3 shows a component schematic of the irradiator, including power supplies, x-ray tubes, cooling system, cables and hoses, as well as interlocks and dosimetry.

Fig. 4 outlines the construction process starting with the original cabinet, which was supplied with 6.35 mm lead shielding. Initial testing indicated that the walls leaked in general at full power (100 KeV, 10 mA), the shielding over the cable hole leaked, and the door leaked badly. An additional 6.35 mm of lead was glued to the walls on all sides and covered with 16 gauge aluminum mesh. Lead strips were added at the top and bottom of the door (Fig. 4(a)). After feeding all required cables and hoses through the opening (b) a shielded tunnel with a 90 degree bend was overlaid (c) and a second cabinet floor installed over the tunnel (d). Top and side views of the tube mounting system constructed from aluminum T-slotted framing are shown in (e). The tube mounts can slide along the tracks, allowing minimal source to sample distance, which is critical for maximizing dose. Also shown in the side view is the rotating chuck for mounting the sample holder. For higher volume cylindrical samples, such as containers of insects, a piston driven system allows the sample to rotate in the horizontal axis while also moving up and down along the vertical axis providing a more uniform dose distribution. This apparatus can be seen in Fig. 2(a), but is not shown in Fig. 4. After mounting the x-ray tubes and hooking up all cables and hoses (f), shielded sliding doors were installed (g) to supplement the original door (g) and ensure no x-rays escape the cabinet.

For the single and double tube models (Figs. 5 and 6) cabinets were custom built in the lab using a “box in a box” design. This basic design was found to be favorable for a number of reasons. First, it is very forgiving of leaks at the box edges where the pieces may not fit perfectly together, since there is a second layer of protection to pick up whatever x-rays escape. For a single layer enclosure, lead sheets are soldered together at the edges and corners. This is a difficult and potentially hazardous task that requires special equipment and expertize. With the box in a box design, each box is composed of six separate sides, constructed as shown in Fig. 7. Lead sheet (3.175 mm) is attached to either side of a plywood core with stainless steel screws, and then overlaid with