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Technical Note

A proposed new configuration of a shuffle-dwell gamma irradiator

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ABSTRACT

A gamma irradiator is a well-developed installation for gamma radiation sterilization. A "shuffle-dwell" mode is preferable for high dose applications. A novel configuration of a shuffle-dwell gamma irradiator is proposed to increase energy utilization and throughput, which would result in higher profitability. While the minimum distance between any irradiation position and each source pencil, the minimum distance between the neighboring irradiation positions and the size of source pencils are kept the same as the current configuration, the irradiation positions and source pencils are rearranged based on the fact that radiation is emitted in an isotropic fashion. The computational results suggest that the proposed configuration requires an 8.7% smaller area and exposes the product to 11.8% more gamma radiation in a 10.7% shorter irradiation time. In other words, the proposed configuration needs a smaller area and shorter irradiation time to have a better performance compared to the current shuffle-dwell gamma irradiator. Note that the claim is based primarily on an analytical calculation. Experimental and manufacturing among other practical considerations will be taken into account in the future work to exhaustively evaluate the performance of the proposed configuration and to compare it with that of the traditional configuration.

1. Introduction

Gamma sterilization is a well-established technology, and it has become a popular sterilization method for syringes, surgical gloves, gowns, masks, dressings, artificial joints, and food packaging [1–3]. Radiation has been employed to effectively sterilize personal protective equipment that is in high demand during the COVID-19 pandemic [4]. Cobalt-60 (^{60}Co) is commonly used as a gamma-emitting source for industrial processing of irradiation. As ^{60}Co naturally decays, two photons—with the energy of 1.17 MeV and 1.33 MeV—are emitted and are used to sterilize various products in a ^{60}Co gamma irradiator. More than 200 industrial gamma irradiators are in operation worldwide with similar configurations [5–7]. In a typical irradiation room, source pencils consisting of slugs of ^{60}Co are loaded in predetermined positions in source modules which are then distributed over a source rack in the irradiator. For continuous irradiation, the products are passed around the radioactive source rack on a conveyor belt. The radiation dose received by a product is a function of the design of the irradiator, the activity of the sources, the density of the products, and the time spent in each position around the source rack. A product may be moved into an irradiation room while the sources are fully shielded (batch operation) or while the sources are not shielded (continuous operation), and the latter is preferable for better throughput. For high dose applications, a product stays in a designated irradiation position around the radioactive source rack for a certain amount of "dwell time" and then moves (shuffle) to the next position. This is called a "shuffle-dwell" mode. Fig. 1 shows a typical movement sequence of products around a source rack at a single level in a shuffle-dwell irradiator [8]. Each product stops at each of the 28 positions for a certain amount of time in sequences, before exiting the irradiation room. The distance between any position and any source pencil is set to be at least 20 cm, and the distance between any two positions is at least 40 cm. The source rack is composed of 14 source pencils, and the distance between neighboring source pencils is set to be 10 cm.

Several studies have proposed ideas to optimize the arrangement of available source pencils with different activities [9–11]. A mathematical model has been proposed to improve the design of a gamma irradiator as a function of its efficiency and parameters of the irradiation process [12]. In addition, a new gamma irradiator that avoids the traditional maze configuration has been constructed in Brazil [13]. Taking into account the fact that currently only about 30% of the energy emitted by ^{60}Co is usefully absorbed by the products [5], this study proposes a novel transport system of a

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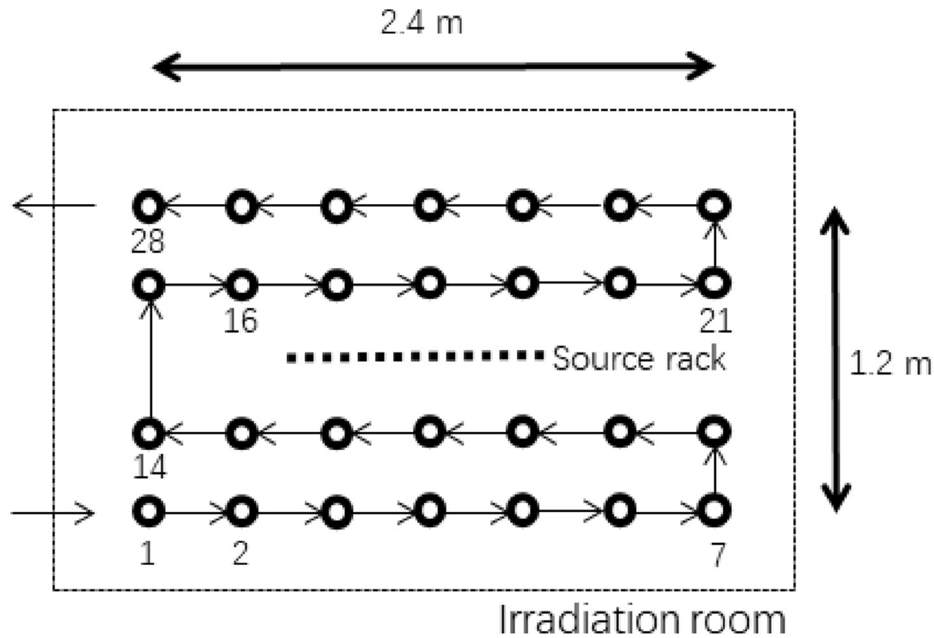

Fig. 1. A bird's eye view of a sequence of movement of products around a source rack (the dashed line in the center) for four passes at a single level for a shuffle-dwell irradiator. The circles and arrows indicate the designated irradiation positions and the directions of movement, respectively.

shuffle-dwell irradiator to increase the efficiency of energy utilization and throughput. Such a system would result in higher profitability by allowing the product to possibly absorb the desired dose in shorter irradiation time.

2. Method

Considering that high energy photons are emitted in an isotropic fashion, a new configuration is designed using five circles. Three of them are centered at (0, 22 cm) with different radii, 22 cm, 62 cm, and 102 cm, and the other two circles are centered at (0, −22 cm) with two different radii, 22 cm and 62 cm. The radii are determined using the condition of the current configuration for comparison: the distance between the center of any irradiated position and the center of any source pencil is kept at least 20 cm, and the distance between the centers of neighboring positions is kept at least 40 cm. The 14 source pencils are placed equally around the centers, (0, 22 cm) and (0, −22 cm) i.e., 7 source pencils on each

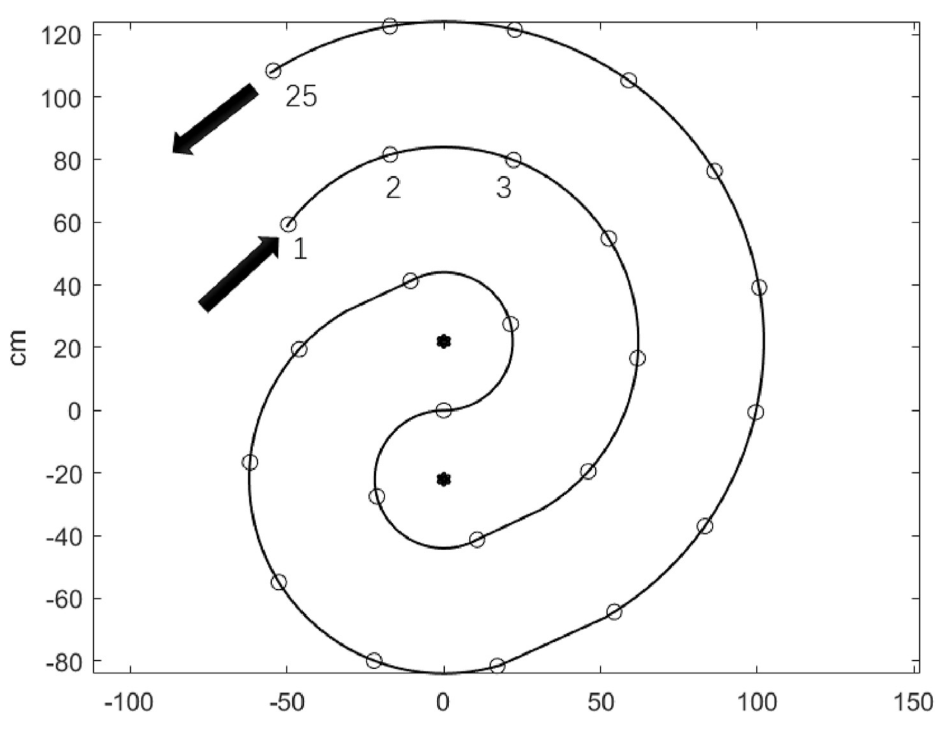

Fig. 2. A bird's eye view of a sequence of movement of products around sources around (0, ±20) at a single level for the novel configuration of a shuffle-dwell gamma irradiator. The circles and arrows indicate the designated irradiation positions and the directions of movement, respectively.

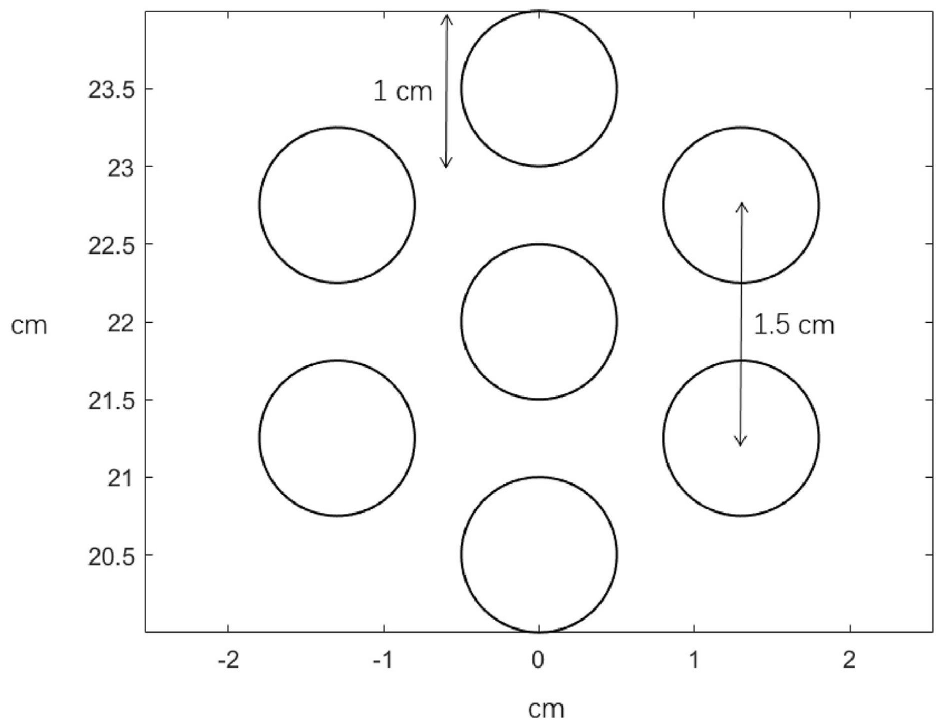

Fig. 3. A bird's eye view of the arrangement of source pencils (the circles) around (0, 22 cm) in Fig. 2.

side and the distance between any source pencil is set to be at least 0.5 cm. The new configuration is sketched in Fig. 2 with the arrangement of 7 source pencils around (0, 22 cm) illustrated in Fig. 3. The arrows show the direction of the products entering and exiting the irradiation room. The circles on the curve indicate the irradiation positions. Note that there are only 25 irradiation spots for the new design, while there are 28 spots for the current design. In addition, the arrangement of the source pencils for the new configuration is different from that for the current practice, while the configurations of the source hoist mechanism and the shielded storage room remain unchanged.

3. Result and discussion

The absorbed radiation dose of a product is proportional to the amount of exposure, which is adopted to compare the performance of the irradiators in this study. Three factors of the current and new configurations are computed and discussed in this section. They are the exposure time in which a product goes through all designated irradiation positions around the radioactive sources, the amount of exposure that the product would receive during the exposure time, and the area of irradiation. A superior design should result in more exposure in less exposure time with a smaller area of irradiation. The computation uses 14 source pencils with a diameter of 1 cm and a length of 45 cm. The activity of each ^{60}Co is 3.7×10^{14} Bq. A product stays at each of the irradiation positions for 1 min and then moves on to the next position. With a similar distance between irradiation spots and the product moving from one position to the next at a similar speed, the exposure time of the new configuration is shorter by about 10.7% as it has only 25 irradiation spots while the current configuration has 28 spots. The rate of the amount of exposure is computed using Eq. (1) [14],

$$\dot{X} = \Gamma \frac{A}{d^2} \tag{1}$$

where Γ is the exposure rate when a radioactive source of 1 Ci is 1 m away (R/h), and it is 2.56×10^{-18} C m^2 kg^{-1}·Bq^{-1}s^{-1} for ^{60}Co. A is the level of radioactivity of the radiation source (Bq), and d is the distance between the radioactive source and the point of calculation. Integrating Eq. (1) to calculate the exposure rate at point M from a pencil source (Fig. 4) we get

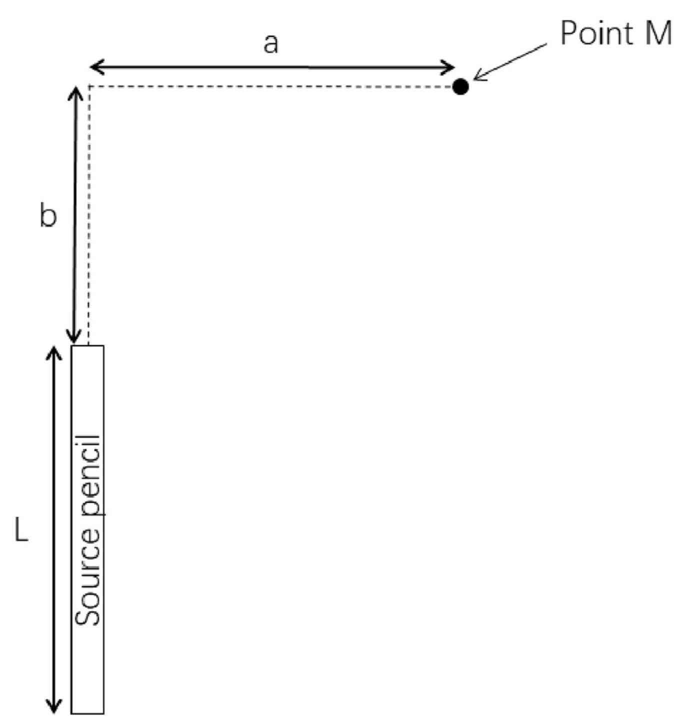

Fig. 4. A side view of a source pencil and a product point to illustrate the calculation of the dose rate. L stands for the length of the source pencil. a and b stand for the distance between the product point and the top of the source pencil, respectively.

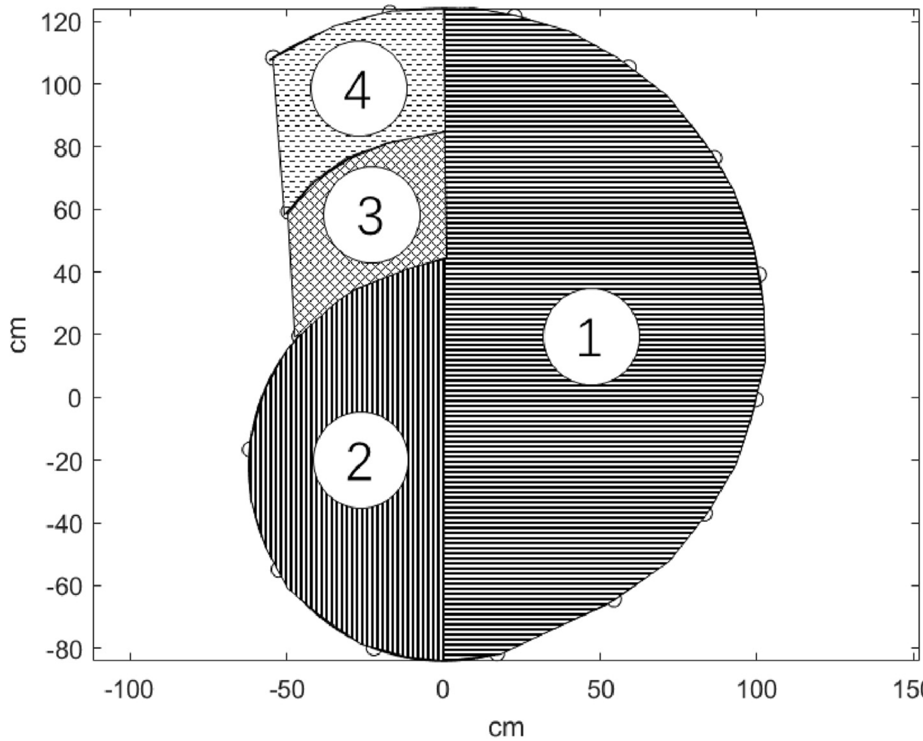

Fig. 5. The area of the new configuration is divided into four sub-areas.

$$\int_{b}^{L+b} \dot{X} dz = \int_{b}^{L+b} \Gamma \frac{A}{d^2} dz \tag{2}$$

where L stands for the length of the source pencil, and a and b stand for the distance between the product point and the top of the source pencil, as shown in Fig. 4. Since $d^2 = a^2 + z^2$, Eq. (2) can be written as

$$\dot{X}L = \int_{b}^{L+b} \Gamma \frac{A}{a^2 + z^2} dz \tag{3}$$

Using $\int \frac{dz}{a^2+z^2} = \frac{1}{a} tan^{-1}\left(\frac{z}{a}\right)$ we get

$$\dot{X} = \frac{\Gamma A}{aL}\left[tan^{-1}\left(\frac{L+b}{a}\right) - tan^{-1}\left(\frac{b}{a}\right)\right] \tag{4}$$

In this study, b is set to be zero, and therefore,

$$\dot{X} = \frac{\Gamma A}{aL}\left[tan^{-1}\left(\frac{L}{a}\right)\right] \tag{5}$$

Assuming gamma-rays are emitted from the center of a source pencil, it is found that the sum of the centers of the 25 irradiation spots of the new configuration is larger than the sum of the centers of the 28 irradiation spots of the current configuration by about 11.8%.

Finally, the irradiation areas of the current and proposed configurations are computed and compared. The area of the new configuration is divided into four sub-areas and illustrated in Fig. 5. Area 1 is considered as a half of the circle with a radius of 102 cm; Area 2 as half of the circle with a radius of 62 cm; Area 3 and Area 4 as parallelograms. It is found that the area of the new configuration is smaller than the current one by about 8.7%. The proposed configuration needs a smaller area and shorter irradiation time to have a better performance compared with the current shuffle-dwell gamma irradiator. Note that the claim is based primarily on an analytical calculation. Experimental and manufacturing among other practical considerations will be taken into account in the future work to exhaustively evaluate the performance of the proposed configuration and to compare it with that of the traditional configuration.

4. Conclusions

A configuration of a shuffle-dwell gamma irradiator is proposed. The irradiation spots and source pencils are rearranged based on how isotopes emit radiation to increase energy utilization, throughput and profitability. The computation suggests that the novel configuration results in about 11.8% more exposure with about 10.7% shorter irradiation time with the same minimum distance between any irradiation position and each source pencil, the same minimum distance between the neighboring irradiation positions and the same size of source pencils. In addition, the area is also about 8.7% smaller compared with the current configuration. In other words, the proposed configuration needs a smaller area and shorter irradiation time to have a better performance compared to the current shuffle-dwell gamma irradiator.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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