Computer simulation to determine food irradiation dose levels

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Abstract. This study provides the algorithm for the estimation of the dose absorbed by minced trout and pieces of chilled trout during 1 MeV electron irradiation. The algorithm uses programming code GEANT 4 based on Monte-Carlo method. The simulation takes into account the electron spectrum as well as the geometry samples. Ferrous sulfate (Fricke) dosimeter and film dosimetry were used to check the algorithm and control the dose parameters during irradiation. The difference between dose rate measured by Fricke dosimeter and simulated dose rate was less than 8 %. The difference between dose rate measured by dosimetric films and simulated dose rate was less than 12 %. The suggested dose estimation algorithm proved to be effective as it successfully determined the dose absorbed by minced trout and pieces of trout. Dosimetry systems can only control the parameters during irradiation treatment. This algorithm can be used to determine the irradiation dose for a product of various geometry, substance, and density.

1. Introduction

These days radiation technologies are in demand in different areas of life. They are used to diagnose and treat various medical conditions, to insure the microbiological safety in medicine and food industry as well as to increase shelf life of foodstuff, to increase the crop yield and to create a new generation of polymers [1, 2].

To increase shelf life of foodstuff it is necessary to maintain organoleptic, physical and chemical properties of foods and to put down the growth of pathogens. The irradiation doses used for treatment of various types of food differ depending on the type of a product. For example, gamma irradiation at the dose 3 kGy is used to control the microbial and safety biochemical parameters of Rainbow trout for up to 4 weeks at refrigerator temperature [3]. Another study concludes that electron beam irradiation of fish preserve at 3–6 kGy extends their shelf life up to 185 days [4]. The irradiation doses 1.0 and 1.5 kGy might be used for shelf life extension of strawberries up to 8 days [5].

There are a lot of articles which focus on the combination of the different physical and chemical treatments on products to achieve the most effective preservation. The combined effects of ultraviolet irradiation, modified atmosphere packaging, and cold storage temperature can improve the microbial safety and extend the shelf life of cherry tomatoes during 9 days of storage [6]. The combination of
frozen storage and 3–5 kGy gamma irradiation results in greater overall reductions on microbial loads, extending shelf-life of poultry [7].

High-dose irradiation may cause changes in the structural integrity and texture of a product. On the other hand, low doses do not inhibit pathogenic microflora and consequently do not increase its shelf life [8–13]. Therefore, it is important to determine the food irradiation doses specifically for each particular goal of treatment.

Dosimetric parameters in foodstuff treatment are controlled using standard methods such as film dosimetry, thermoluminescent dosimeter, EPR dosimeter, chemical dosimetry methods [14–22]. Dosimetric systems can monitor the repeatability of the dose distribution and help to determine the most efficient irradiation method [16, 18, 19].

This study provides the algorithm for the estimation of the dose absorbed by a chilled trout during 1 MeV electron irradiation. This algorithm can be used to determine the irradiation dose for a product of various geometry, substance, and density.

2. Materials and Methods
The algorithm uses GEANT 4 source code based on Monte-Carlo method. The code represents the C++ database which includes the description of all known particles and physical processes that occur when particles interact with a substance. Built-in GEANT 4 tools allow describing the experiment in terms of geometry and chemical composition of an object. GEANT 4 is used in high energy physics and nuclear physics as well as space researches and medicine.

An experiment was conducted using an electron treatment method on two types of chilled trout samples. The first type was 0.5 ml minced trout homogenate placed in 2 ml Eppendorf tubes. After irradiation homogenate was used to monitor microbiological parameters of minced trout during the storage. The second type of samples was thin slices of trout in vacuum bags. They were used to control the changes in taste, odor, and texture of chilled trout after irradiation.

Samples were treated by 1 MeV electron beam using the industrial electron accelerator UELR-1-25-T-001. The distance between the output beam and the duralumin plate with samples was 12 cm (figure 1). Each time during electron treatment the total charge absorbed by the plate and irradiation time were monitored to determine the required dose of irradiation. The samples were irradiated with 5 different doses.
3. Results and Discussion

The computer simulation took into account the electron spectrum (figure 2) as well as the geometry of the duralumin plate and samples placed on it (figure 1). We used a 35 cm long, 3 cm wide and 0.8 cm thick parallelepiped plate. The number of electrons in the beam was $Q_{model}=10^8$. The fish was simulated as a water phantom since the density of the fish and water are practically the same.

Figure 1. Minced trout (a) and chilled trout irradiation method (b).

Figure 2. The electron spectrum $N(E)$ of the accelerator UELR-1-25-T-001.
The dose absorbed by samples with water was determined using the following formula:

\[ D_{\text{model}} = \frac{\Delta E_{\text{model}}}{M_{\text{model}}} \]  

where \( \Delta E_{\text{model}} \) is the energy absorbed by water, \( M_{\text{model}} \) is the mass of the water layer.

The dose absorbed by the samples was proportional to the charge \( Q \) absorbed by the duralumin plate used in the simulation. Dose absorbed by the samples considering the experimental charge \( Q_{\text{exp}} \) absorbed by duralumin plate measured during irradiation was determined using the formula:

\[ D_{\text{sample}} = \left( \frac{Q_{\text{exp}}}{Q_{\text{model}}} \right) \times D_{\text{model}}. \]

The computer simulation model of homogenate was based on 39 mm long, 1 mm thick polypropylene cylindrical samples 9 mm in diameter. Minced trout homogenate was simulated as 0.5 ml water. The thickness of the water layer was 3 mm. The distance between the output beam and the duralumin plate with samples was 12 cm (figure 3). Dose Rate was determined as 1.84 Gy/sec.

![Figure 3](image-url)  
**Figure 3.** Computer simulation of 1 MeV irradiation treatment of water phantom. Red lines are electrons, green lines are photons, white cylinders are tubes with water.

Ferrous sulfate (Fricke) dosimeter was used to check the algorithm. The 0.5 ml of the Fricke solution was irradiated in 2 ml Eppendorf plastic tubes, the radiation method corresponded to the irradiation of samples with minced trout homogenate. The actual doses absorbed by the dosimetry solutions were measured by the change in their optical densities using spectrophotometer Shimadzu UV-3600. The operating wavelength was 304 nm. Thus, the absorbed dose \( D_{\text{Fricke}}^{\text{calc}} \) was determined using the formula:

\[ D_{\text{Fricke}}^{\text{calc}} = \left( k \Delta S \right) / \left[ \rho G(\text{Fe}^{3+}) \varepsilon l \right], \]

where \( k = 9.65 \cdot 10^6 \), \( \Delta S \) is the difference in absorbance between the irradiated and non-irradiated Fricke solutions at 304 nm, \( \rho = 1.024 \text{ g/cm}^3 \) is the density of the dosimetry solution, \( G(\text{Fe}^{3+}) = 14.4 \) molecules per 100 eV is the radiation yield of ferric ion, \( l = 1 \text{ cm} \) is the optical pathlength and \( \varepsilon = 2160 \text{ l/(mol} \cdot \text{s}) \) is the molar linear absorption coefficient of the ferric ions.

The density of minced trout homogenate \((0.994 \pm 0.05) \text{ g/cm}^3\) is practically similar to the density of ferrous sulfate solution \((1.024 \pm 0.05) \text{ g/cm}^3\). Using computer simulation the water phantom in cylindrical polypropylene tubes of the same geometry was replaced with the Fricke solution, in which the absorbed dose \( D_{\text{Fricke}}^{\text{model}} \) was calculated in the same way as in the water phantom. The simulation allowed to estimate the conversion rate of the absorbed dose in the dosimetry solution \( D_{\text{Fricke}}^{\text{model}} \) into the absorbed dose in the water phantom: \( D_{\text{water}} = 1.01 \cdot D_{\text{Fricke}}^{\text{model}} \). Considering that the dose measured by the dosimeter was practically similar to the dose absorbed by minced trout homogenate.

The dose rate measured by Fricke dosimeter was \((1.7 \pm 0.04) \text{ Gy/sec}\). The difference between measured and simulated dose rates was less than 8 %. During the experiment, thin slices of trout in vacuum bags were irradiated from two opposite sides to achieve the irradiation uniformity. The computer simulation model of pieces of chilled trout was based on 100 mm long, 8 mm thick and 28 mm wide parallelepiped water plate surrounded by polypropylene 0.1 mm thick. Water phantom was divided into 8 layers 1 mm thick (figure 4). The algorithm allows determining the dose distribution in water phantom. The total dose \( D_{\text{phantom}} \) absorbed by the water phantom was calculated as the sum of doses absorbed by each layer \( D_{\text{layer}} \). \( D_{\text{layer}} \) was determined using the following formula:
where $dE_{layer}$ is the energy absorbed by the water layer, $dm_{layer}$ is the mass if the layer. The total dose $D_{phantom}$ was calculated as

$$D_{phantom} = \frac{\sum_{i=1}^{N} dE_{layer}}{M_{phantom}},$$

where $M_{phantom}$ is the mass of water phantom.

Figure 4. Computer simulation of 1 MeV irradiation treatment of water phantom. Red lines are electrons, green lines are photons, a white parallelepiped is water phantom.

Figure 5 shows the dose distribution in water phantom during 1 MeV electron irradiation.

It was found that doses absorbed by slices of trout were 0.25 kGy, 0.5 kGy, 1 kGy, 3 kGy, and 6 kGy. Films dosimetry was used to check the dose estimation algorithm for pieces of trout. Each time during irradiation 10–12 mm long, 43–45 mm wide dosimetric films SO PD(A) -1/10 were placed on thin slices of trout. The actual doses absorbed by the dosimetric films were measured by the change in their optical densities using spectrophotometer Shimadzu UV-3600. The operating wavelength was 550 nm. Thus, the absorbed dose $D_{film}^{calc}$ was determined using the formula:

$$D_{film}^{calc} = 8.10 \times A^{0.981},$$

$A$ is the difference in absorbance between the irradiated and non-irradiated films at 550 nm.
During computer simulation, dosimetric films were placed on the parallelepiped water plate. The difference between measured and simulated dose rates absorbed by dosimetric films was less than 12%.

4. Conclusions
The suggested dose estimation algorithm proved to be effective as it successfully determined the dose absorbed by minced trout and pieces of trout. The reliability of the algorithm was checked using films and chemical dosimetry.

Dosimetry systems can only determine the dose absorbed by a product during irradiation treatment if the geometry, substance, and density are similar to those of the actual product. Considering that it is impossible to insure such conditions in real-life irradiation treatment, the algorithm can be used to find the dose absorbed the actual product. To achieve consistent irradiation treatment values it is essential to control the absorbed dose properly during treatment.

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Acknowledgments
The reported study was funded by RFBR, project number 18-016-00198a.