# Properties of hens’ eggs after surface irradiation by nanosecond electron beam

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***Abstract*—Irradiation experiments were carried out by means of the pulsed repetitive nanosecond accelerator URT-0.5 (electron energy of up to 500 keV, a pulse duration of 50 ns, pulse repetition rate up to 200 pps. The electron average dose rate on the egg surface was 200 Gy/pulse and the instantaneous dose rate was 4 GGy/s. Thermoluminescent dosimeters, TLD-500, were used to determine the distribution of the bremsstrahlung dose inside hens’ eggs. It has been established that for nanosecond electron beam irradiation with dose higher than 5 kGy sufficient for complete disinfection on the hens’ egg surface, due to bremsstrahlung, the dose inside it will not exceed 0.08 Gy. This dose value should not lead to biological changes in the white or yolk. Dose 5 kGy does not influence the observed shell surface; there are no changes on the egg surface according to scanning electron microscope data. For heavy doses, rounded areas of the surface relief are observed. Data from energy-dispersive X-ray spectroscopy analysis for high dose show a significant increase in the amount of phosphorus and especially calcium in the shell and some reduction in the amount of oxygen, most likely due to change in the surface distribution of elements in the shell.***

***Keywords—disinfection, electrons, bremsstrahlung, dosimetry, radiation treatment, hens’ egg.***

## I. Introduction

At present, the only way to reduce the microbiological contamination of foods is virtually heat treatment. However, thermal sterilization leads to irreversible changes in the properties of raw materials, which are not always acceptable. Applied chemical methods, such as salting, sugaring, etc. lead to the same result, and use a lot of preservatives. Therefore, heat pasteurization followed by cooling to temperatures at which the multiplication of microorganisms is difficult, is widely used to increase the shelf life of foods.

It is known that one of the indicators of the eggs quality is the cleanliness of the shell. However, the presence of dirt (i.e., microorganisms) not only makes the appearance of the eggs unattractive, but also facilitates the penetration of microorganisms through pores in the shell egg into its content, which leads to the rapid deterioration of eggs, and also renders them liable to salmonella infection.

Washing improves the appearance of the eggs, but sharply reduces their storage stability, so it is usually done in the food industry before breaking up the eggs. Such washing procedure in the opening of pores in the shell, through which the microorganisms can penetrate into the egg. It also requires a hot water flow (~ 80ºC) and chemically disinfecting substances (2-3 % hydrogen peroxide), which greatly increases environmental pollution by toxic waste.

An alternative is radiation sterilization, due to the universally harmful effects of ionizing radiation on any biological objects. In this way, the absorbed dose (dose) of radiation sterilization (regardless of the type of radiation) does not exceed 25 kGy.

However, the irradiation of the foods may be accompanied by a variety of chemical reactions which may transform the organoleptic properties of the products. Thus, it is necessary to set the limits of dose for irradiation of various products.

For example, for fresh eggs, a level of dose ≤ 3 kGy is recommended [1], which is close to the dose level for de-activation of the bacteria of the Salmonella group [2]. Irradiated foods are marked with a special sign "radura", so that the buyer can choose whether to use irradiated products or not. Unfortunately, radiation phobia is of great importance for consumer choice, therefore it is desirable to create technology enabling motivated refusal of such marking [3].

The disadvantage of irradiation sterilization is its high cost and heightened risk for the working staff. This risk can be significantly reduced by optimizing the radiation source.

To solve the problems of microbiological contamination of eggs and consumer sentiment, in our view, the following approaches look promising.

Firstly, by proper selection of type and energy of radiation, choose a dose distribution profile within the product that will destroy, all kinds of micro-organisms, including pathogenic ones, both on the shell surface and in its pores as well as in the air chamber, right up to the under-shell membranes.

Secondly, ozone will be produced in air under irradiation, which will also contribute to the disinfection of the surface, especially by irradiation of eggs in plastic containers. It is possible to sterilize the eggs after packaging, both by the radiation itself and by the creation of ozone at concentration levels critical to microorganisms in the packaging – radiation-chemical sterilization [4]. It is important that the

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presence of sealed plastic containers allows us to solve the problem of insemination of eggs during storage.

Both ways have their merits. Moreover, in the real technological process, the two ways can be combined in different proportions.

For this purpose, electrons with energy up to 0.5 MeV are the most suitable. At present, nanosecond electron accelerators for technologies [5] which significantly reduce the costs of the radiation source itself, as well as the costs of radiation shield, have been developed and produced.

Furthermore, the stronger bactericidal effect of the nanosecond electron beam (NEB) is known [6]. This makes it possible to reduce the dose level of the electron beam to in half or two thirds, which will increase the efficiency of the method while leaving the energy consumption and material costs the same.

A feature of the NEB spectrum is the presence of a greater proportion of those low-energy electrons when acceleration at the pulse fronts of the accelerating voltage occurs. For our purposes, this is a positive feature, because it allows us to obtain the desired dose distribution profile within the product.

On the basis of these principles, a technology of egg surface disinfection in poultry breeding has been developed [7]. In the treatment of eggs for eating, the dose on the surface was from 5 to 25 kGy, of hatching eggs – 40 kGy. It has been established that the sterilizing dose sufficient for destruction of microorganisms on the surface of eggs in plastic packaging is 5 kGy. In the case of egg treatment with dose exceeding the minimum sterilizing dose by 8 times (40 kGy), significant changes of physical and chemical properties of the white, yolk, air chamber and shell were not observed.

The radiobiological effect was not established, because indicators of hatchability and state of health of the chicks produced from eggs treated by NEB during the first hours of embryo formation did not differ from similar indicators of a control group.

The results given in the report [7] demonstrate the absence of significant differences between indicators of quality of meat from chickens produced from the eggs of the pilot batch subjected to influence of NEB, and chickens produced from eggs of the control batch. The variability of the received results is not high, and apparently is more caused by sexual distinctions and reaction to environmental factors. Signs of radiation damage to egg and germ structures in the experimental group are not detected. The remote influence of NEB radiation of eggs on quality of production it was not established.

For this technology of radiation, the profile of dose distribution in the egg is chosen so that the white is not irradiated with electrons at all. Unfortunately, it is impossible to avoid irradiation of the egg white, since bremsstrahlung is induced by absorption into the electrodes, which makes a major contribution to the dose created inside the egg. However, the efficiency of NEB energy transformation in bremsstrahlung in this range of electron energy is insignificant (less than 1%), especially on targets of the atomic elements with low atomic numbers of which the shell consists.

Thus, the aim of this study was to investigate the profile of dose distribution inside and on the surface of hens' egg from the electron beam and bremsstrahlung, and also to study the extent of radiation damage to a shell after sterilization.

## II. THE METHODOLOGY AND EXPERIMENT RESULTS

The irradiation experiments were carried out by the pulsed repetitive nanosecond accelerator URT-0.5 [8] (electron energy up to 500 keV, pulse duration about 50 ns, pulse repetition rate up to 200 pps). In the first stage, the measurement of the absorbed dose distribution in depth of polyethylene (analog of biological tissue) was carried out by the gray wedge method. Dose was tested by a film dosimeter CO AD (F) R-5/50 [9], covered with polyethylene layers of varying thickness (up to 600 μm).

Dose measurements using a film dosimeter were conducted by determining the density of darkening on the spectrophotometer PE 5400VI, followed by recalculation from calibration graphs. During the experiments, the accelerator was operating at charging voltage mode of 25 and 30 kV (the accelerating voltage of 450 and 500 kV, respectively). Electron beam dosimetry results are shown in Fig. 1.

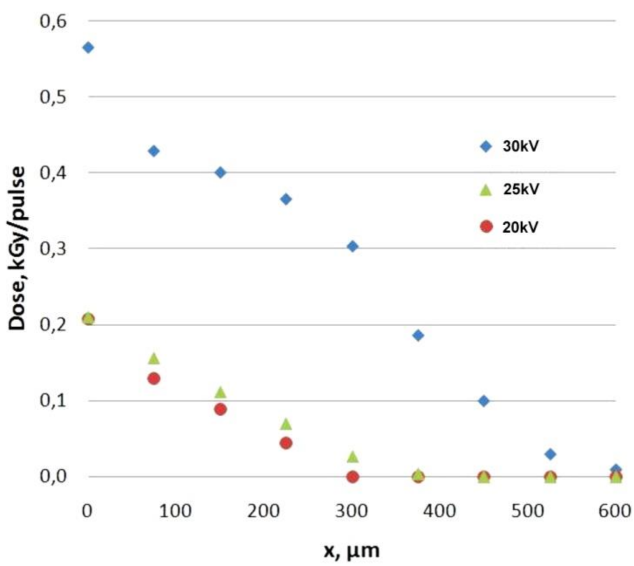



Fig. 1. Distribution of electron beam dose in depth in polyethylene for different charging voltages on the accelerator URT-0.5.

Also using the film dosimeter, a measurement of the electron beam dose on the shell surface (removed from the egg) and under the shell as well as beneath the absorber layer (polyethylene of 80 μm thicknesses) was taken (Figure 2). The sample was placed in a plastic container (the "selection" P-11 type, made of polystyrene to retain the geometry used for the irradiation of the eggs. The results of dosimetry at a different charging voltage are shown in Table 1.

To determine the distribution of bremsstrahlung dose inside a hens' egg, thermoluminescent dosimeters (TLD) TLD-500 (diameter of 5 mm and a thickness of 1 mm) based on aluminum oxide doped with carbon were used. The dosimeters were placed in sections of boiled eggs (cut lengthwise or crosswise), in such a way that it was possible to determine the dose distribution at various points of the biological object (Figure 3).

Dose measurement was carried out by a hardware system for activating TLD dosimeters. Thermoluminescence lines were recorded by a special automatic apparatus at a heating rate of 2 K/s [10]. The signal was detected by a photocopier FEU-142 with reduced sensitivity to thermal radiation of the heater (the maximum temperature could be 1200 K).

For determination of a radiation damage level to a shell subjected to NEB radiation, the shell samples were studied: the original ones and those irradiated by dose 1.5, 5, 25 and 40 kGy on a LEO982 scanning electron microscope (SEM) with dispersive X-ray spectroscopy (EDX) attachment for microanalysis of (accuracy of the quantitative EDX analysis is 0.1-1% depending on elements).

TABLE I. MEASUREMENT RESULTS OF THE ELECTRON BEAM DOSE

| Location of detectors | Dose, Gy/pulse at different charging voltage | | |
|---|---|---|---|
| | *30 kV* | *25 kV* | *20 kV* |
| On the lid of a plastic container outsid | 583 | 505 | 173 |
| On shell surface | 195 | 170 | 8 |
| Under shell | 8.43 | -[a] | - |
| Under shell and absorber layer | 0.61 | - | - |

[a] Dose value is below the threshold of detector sensitivity

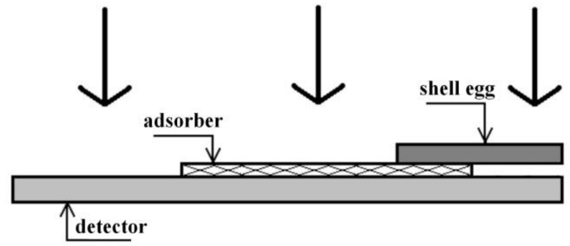



Fig. 2. Geometry of irradiation by electron beam for dosimetry.

Results of shell microscopy for different doses are given in Figs. 4 and 5, results of EDX analysis in Table 3 and Figs. 6 and 7.

## III. DISCUSSION OF THE MEASUREMENT RESULTS

As one can see from Fig. 1, by varying the charging voltage of the accelerator, it is possible to choose the depth of electron penetration in order to limit the exposure of the shell (0.3-0.4 mm) and the under-shell protein membranes (~ 70 µm). At the same time, it is possible to avoid radiation of the edible part of the egg.

It should be noted that the shell consists of calcium carbonate with a density (2.74-2.83 g/cm$^3$) and an atomic number close to those of aluminum. However, the shell is a porous structure and the passage of electrons through it will be a complex process.

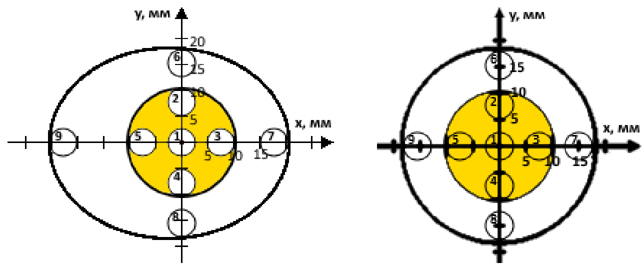



Fig. 3. Placement of TLD dosimeters (diameter 5mm) in hens' egg in vertical (right) and horizontal section.

TABLE II. MEASUREMENT RESULTS OF BREMSSTRAHLUNG DOSE INSIDE THE EGG

| | Dose, mGy/pulse | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **# dosimeter** | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* | *9* |
| ***Horizontal section*** | 1,3 | 2,5 | 1,8 | 1,7 | 1,5 | 1,8 | 3,1 | 1,5 | 1,7 |
| ***Average value*** | 1.3 | 1.87 | | | | 2 | | | |
| ***Vertical section*** | 1,6 | 1,5 | 1,7 | 1,3 | 1,4 | 1,8 | 2,1 | 1,5 | 2,6 |
| ***Average value*** | 1.6 | 1.47 | | | | 2 | | | |

The data of Table 1 show that at the charging voltage of 30 kV, it is possible to obtain the desired profile of the absorbed dose distribution at a depth to which the electron irradiation does not penetrate below the absorber layer, simulating the under-shell egg membranes (Fig. 2).

At the same time, the average electron beam dose on the surface of the eggs was 0.2 kGy/pulse (see Table 1) and the instantaneous dose rate was 4 GGy/s. Consequently, at dose 5 kGy, which consists of 25 pulses and is sufficient to full disinfection of the surface of eggs from Salmonella, bremsstrahlung dose in the white will not exceed 50 mGy and 47 mGy in the yolk (see Table 2).

This dose value should not lead to biological transformations of the biological tissue [11], but on the contrary, is within the dose range that has a stimulating effect on the living organisms (radiation hormesis) [12]. It is also confirmed by results of the work [7].

Bremsstrahlung yield calculations under the irradiation surface of the egg (4.5 cm in diameter) by electron beam from an accelerator URT-0.5 (electron current density per pulse ~ 3 A/cm$^2$), were made according to Foster's formula [13]. The results show that the dose is within the range 1.1-1.5 mGy/pulse. Additional irradiation of the eggs was created by the electron beam bremsstrahlung, being absorbed by the radiation-absorbing accelerator output structures, as well as by scatter radiation.

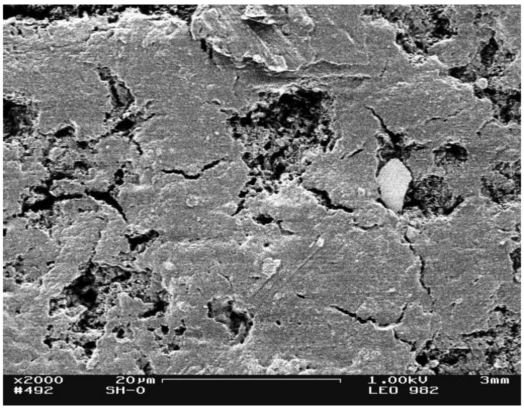
TABLE III. CONTENT OF ELEMENTS IN A SHELL DEPENDING ON DOSE BASED ON EDX ANALYSIS RESULTS

| Element, wt% | Dose, kGy | | | | |
|---|---|---|---|---|---|
| | *0* | *1.5* | *5* | *25* | *50* |
| O | 83.74 | 87.33 | 88.14 | 72.69 | 73.08 |
| Mg | 2.95 | 2.37 | 3.09 | 4.09 | 3.19 |
| Al | 3.36 | 3.52 | 2.11 | 0.53 | - |
| Si | 0.71 | 0.82 | 0.59 | 0.42 | - |
| P | 2.83 | 2.33 | 2.58 | 6.21 | 4.91 |

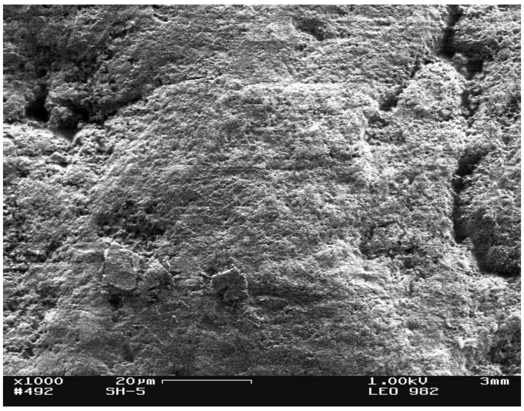
| Element, wt% | Dose, kGy | | | | |
|---|---|---|---|---|---|
| | *0* | *1.5* | *5* | *25* | *50* |
| S | 0.31 | - | - | 0.75 | 0.84 |
| Ca | 6.10 | 3.63 | 3.50 | 15.32 | 17.99 |

From the results of shell microscopy in Fig. 4, it is possible to draw the conclusion that low dose values (1.5 and 5kGy) do not make any visible impact on the surface; changes of a surface appearance are not observed.

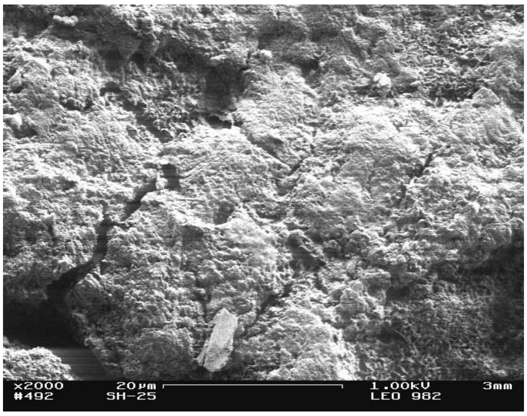
**0 Gy**




**5 kGy**




**25 kGy**




**40 kGy**

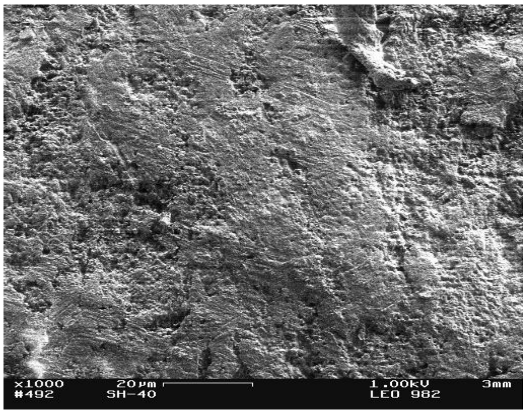
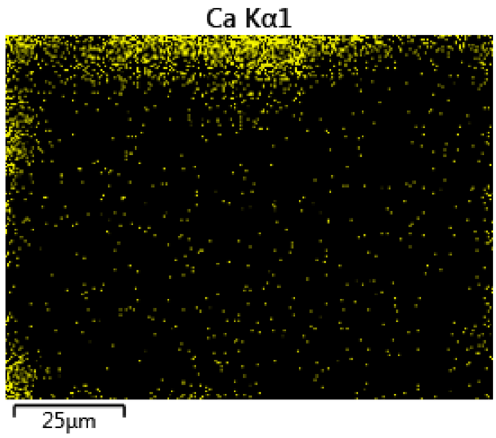


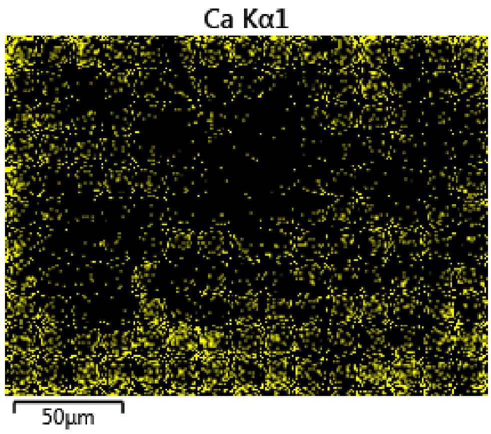

Fig. 4. External appearance of shell for different dose.

From the data in Table 3 it is apparent that at such dose, quantitative change of the shell element structure that matches the data of the chemical analysis of a mass fraction of calcium and phosphorus in a shell as in work [7] is not established.

**0 Gy**




**25 kGy**



**40 kGy**

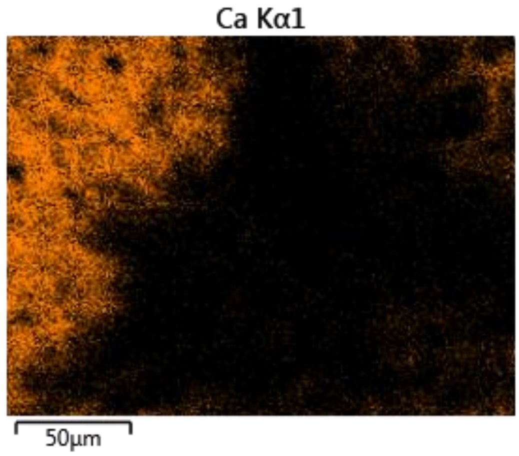
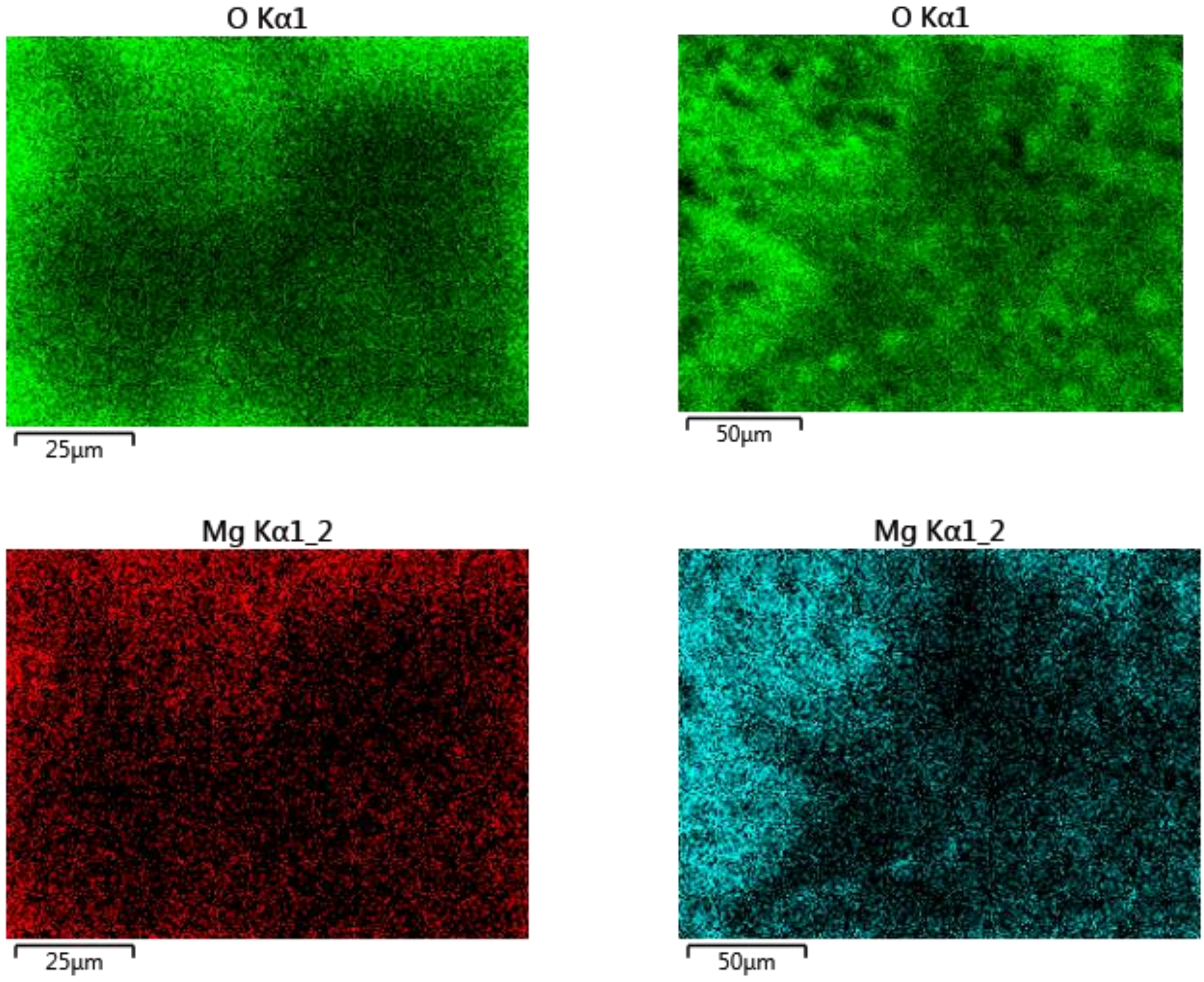



Fig. 5. Calcium distribution for different dose.

At increase of dose to 25 kGy (Fig. 5a and b), smoothed areas of the surface relief are observed. The shell appears to be melting or underdone. The same areas, but in greater quantity, are also observed in Fig. 5c and 5d at dose 40 kGy. It should be noted that with increase of dose, the surface of a shell becomes more smooth. The obtained data are consistent with the data of [7], in which it is noted that by results of the macroscopic analysis of qualities of incubatory eggs at dose 40 kGy, the quantity of points and rods on a shell increases to 80% (for control 53%).



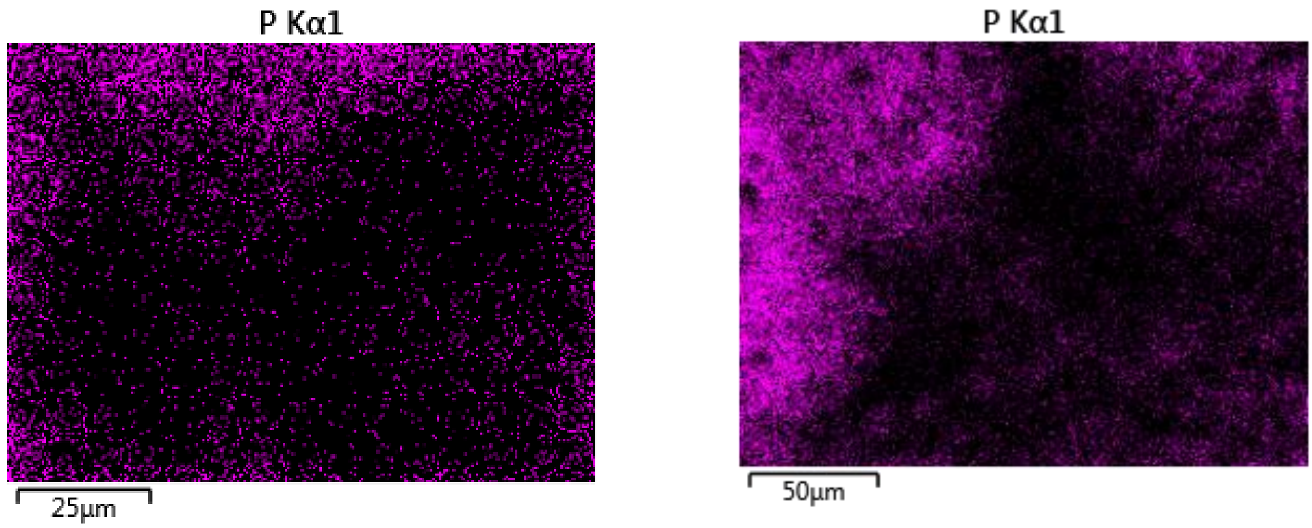



Fig. 6. Oxygen, magnesium and phosphorus distribution at 0 (left) and 40 kGy.

Results of the surface EDX analysis show (Fig. 6) that in all shell samples, calcium is not distributed evenly and dependences of this distribution on dose level are not observed; the dependence is observed from the chosen sector of a shell. The fairly even distribution of other elements – oxygen, magnesium and phosphorus – also begins to be disturbed, primarily for phosphorus, only at dose 40 kGy (Fig.7).

The data in Table 3 at high dose show a qualitative change in the amount of phosphorus and especially calcium in the shell, with some reduction of oxygen content.

Possibly, the difference between our data and data of work [7] on calcium and phosphorus is connected with the change in the spatial distribution of elements on the shell (see Figs. 6 and 7), which does not show up in the quantitative analysis.

## IV. Conclusion

The results obtained enable the conclusion to be drawn that it is possible to isolate some NEB radiation conditions in which the profile of dose distribution in the egg excludes protein radiation by electrons.

It has been established that irradiation by an electron beam with dose level of 5 kGy is sufficient for the full disinfection of the surface of an egg. At the same time, the dose inside the egg will not exceed 80 mGy because of bremsstrahlung. This dose value should not lead to biological transformations of the white and the yolk.

It was found that dose 5 kGy does not have any visible impact on the surface of a shell; changes of a surface appearance are not observed. At high doses, smoothed areas of the surface relief are observed.

Data of EDX analysis at high dose show a significant increase in amount of phosphorus and especially calcium in a shell, with some reduction of oxygen content, most probably due to change of the spatial distribution of elements in a shell.

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