EFFECT OF HETEROGENEITY OF SUBJECTS OF INDUSTRIAL IRRADIATION PROCESSES ON SPATIAL DISTRIBUTIONS OF ABSORBED DOSES UPON ELECTRON BEAM, X-RAY AND GAMMA IRRADIATION

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By means of Monte Carlo computer modeling the effects of heterogeneity and spatial arrangement of irradiated disposable syringes on the absorbed dose deposition profiles has been studied for different kinds of irradiation. Substantial deviations from the predictions of conventional approximation of homogenized medium have been found for electron beam irradiation. The dependencies of irradiation process parameters on the orientation and the regularity/stochasticity of the product loading pattern, the variations of dose accumulation in component parts of a syringe and the non-equilibrium dose effects on the internal surface of a syringe needle have been investigated.

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Relativistic beams of electron accelerators and gamma quanta from nuclear decay of radionuclides are extensively used worldwide in various industrial irradiation processes. Among them the most important are the radiation sterilization of medical items (syringes, blood transfusion systems etc.), food irradiation and so on [1].

Certain kinds of irradiated products (medical items, packaged food, electric cables etc.) are substantially heterogeneous. The effects of products heterogeneity on the absorbed dose deposition are of keen interest for operators and users of industrial irradiation processes from the point of view of their reliability and optimality. Besides for such an applied problem the heterogeneity effects are valuable for mainstream directions of the developments in theoretical dosimetry and experimental techniques based on interaction of radiation with solid.

Currently the tendency of application of quantitative methods of mathematical modeling of the transport of electrons and photons in condensed media is exhibited in the irradiation industry [2, 3, 4, 5]. Being validated by the intercomparison with experimental dosimetry they become a constituent of international regulatory documents that establish the standard practices of industrial irradiation processes development and support [6, 7]. The most adequate for these applications are the Monte Carlo methods due to their capability to take into account the complex structure and composition of irradiated products and to provide precise calculation of beam energy deposition in heterogeneous systems.

The present paper deals with the study of the heterogeneity effects in representative subjects of industrial irradiation by means of the in-house developed Monte Carlo computer code *RaT* based on the CERN *Geant4 OO Toolkit* class library [8]. The *RaT* code inherits the extensively validated *Geant4* physical models of electromagnetic interactions of charged particles and photons with media, provides a user-friendly framework for development of complex 3D models of radiation sources and irradiated products and effective algorithms of handling with large arrays of these models, the tools for deep analysis of modeling results as well as advanced features such as the capability to deal with stochastic 3D geometries for simulation of radiation transport in random media [9].

We recognize the modeling methods to supplement experimental qualification and routine dosimetry and to obtain valuable information especially in cases of intractable problems of direct experimental measurements [2]. Hence this work is focused on the pure effects of product heterogeneity concerning the role of spatial and directional loading patterns of irradiated products, effects of the randomness of their arrangement and variations of the dose accumulation in different component parts of the product unit.

1. MODELING SETUP

As a representative type of product we have chosen disposable syringes, a typical subject of electrophysical technologies of radiation sterilization [1]. Using actual specimen of one of syringe models, the 2 ml insulin syringe, we have developed its detailed 3D model (see Fig.1 that is the VRML output from the *RaT* code 3D geometry engine) to be used in Monte Carlo modeling.

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Polymeric details of a syringe model consist of 0.9 g/cm^3 dense $(CH_2)_n$ polypropylene (PP). The syringe needle (40 mm long and ⌀0.65 mm across diameter) is made of stainless steel with density 7.9 g/cm^3. It has a ⌀0.32 mm concentric hole. The overall spatial dimensions of a syringe unit as it is packaged into the cartridge-belt-like bands are about 8×2.5×1.5 cm.

In industrial sterilization processes plenty of syringes are irradiated simultaneously being placed in cartons according to the more of less fixed loading pattern.

From the computational point of view the development of mathematical model of the dense placement of syringes in containers (the product loading pattern) is non-trivial. The problem arises from the fact that product loading patterns are not completely deterministic and fluctuate from one packaging box to another whereas the deductions made from the results of modeling have to bear relation to the whole irradiation process rather then to the irradiation of specific carton [9].

Fig.1. *3D computer model of disposable syringe*

This problem does not spring up in the commonly used approximation of homogenized medium [2, 9] with effective density and composition. For syringes such a mix (incl. the environmental air) contains 14 chemical elements (H, C, O, Fe, etc.) and, for acceptable degree of unit packaging, has effective density of 0.11 g/cm^3.

To study effects of the product heterogeneity more sophisticated approximations have to be introduced. The simplest one is the assumption of regular loading pattern when syringe units are supposed to form regular 3D lattice. Within the *RaT* code it is implemented using the spatial replication of 3D volumes (see, e.g., Fig.2).

Another characteristic feature of product loading patterns is the orientation of product units with respect to the direction of beam. We considered two limiting cases: the collinear longitudinal orientation (see Fig.2) and the transversal loading when syringe axes are orthogonal to the beam axis direction. In the former case syringes are irradiated from the face while in the latter one the beam exposes flank surfaces of barrels.

The stochastic perturbations of loading patterns at this stage have been introduced in the approximation of random shifts of laterally regular layers of syringes. This algorithm is quite enough to uncouple long-range spatial correlations such as open channels in regular lattices.

Both regular and randomized loading patterns exactly preserve the product unit heterogeneity and conserve the mean density of irradiated medium to be equal to the density of the effective homogenized medium.

To model the radiation transport in randomized loading patterns the advanced double Monte Carlo method proposed in Ref. [9] was used. The stochastic reconstruction of the problem 3D geometry was performed for each primary particle history using the technique of random replications implemented for the first time in the current version of the *RaT* code.

In the present work we have limited ourselves with investigation of the effects of heterogeneity on depth-dose dependencies knowingly neglecting the effects [5] arising at lateral edges of product boxes. For the same reason the packaging box itself also was not included in the computer model. Finally, we did not ventured to model definite industrial irradiators and in order to obtain some general results systematically applied the approximation of a broad beam for all kinds of irradiation.

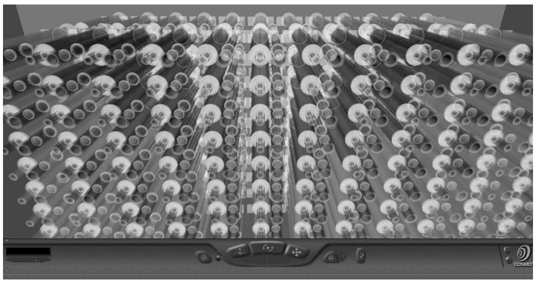

Fig.2. *RaT screenshot of the perspective projection of the regular longitudinal loading pattern of syringes*

Within this approximation the beam was uniformly aimed to the representative unit cell of the transversal plane that falls on one syringe. Other requirements of the broad beam approximation is the sufficient transversal dimensions of the irradiated medium to eliminate all lateral edge effects and the normalization of calculated quantities per unit of primary particles flux.

In view of these requirements in our model the lateral dimensions of product loading patterns spread to 6−8 m. In longitudinal (depth z) direction the thickness of product layer was 80−120 cm subject to the pattern orientation. Thus the whole 3D geometry of the product model contained about 5.7×10^6 of syringe models.

Three kinds of the broad beam irradiation have been considered. The first one represents the direct irradiation by 5 MeV parallel electron beam (EB). We expected the heterogeneity effects to be the most pronounced in this case because the calculated CSDA range of electrons in polypropylene (2.456 g/cm^2 or 2.729 cm at 5 MeV) is much less then the length of a syringe barrel.

The second case is the irradiation by X-ray beam from (e^-, X)-converter driven by the same 5 MeV electron beam. The X-ray production in converter was simulated in detail i.e. the heterogeneous converter model was included into the problem geometry and accelerated electrons were considered as primary radiation. The multilayer model of the optimized water-cooled converter included 50 μm thick Titanium foil of the accelerator beam exit window, 12 cm wide air gap and the converter itself: the 1.2 mm thick Tantalum plate, 2 mm thick layer of liquid water coolant followed by 2 mm of Iron that simulates the cooler casing. In a series of preliminary calculations the photon yields and energy spectra from the converter had been simulated and benchmarked against the manufacturer modeling data as well as against the independent modeling by means of the *XR-Soft* code [4]. The obtained energy conversion efficiency reaches 8.697% (0.9% relative deviation from data of Ref. [4]). The photon spectrum has a broad maximum at 300 keV and agrees quantitatively with the results both of *ITS3* and *XR-Soft* [4] codes simulations.

The last case corresponds to the irradiation by the γ-radiation with bare spectrum of the mix of Europium radionuclides (47% of ^{152}Eu, 51% of ^{154}Eu and 2% of ^{155}Eu). These nuclides have complex broad spectra of decay gammas (photon energies from 121 keV up to 1.408 MeV with mean energy of about 800 keV) and are considered as candidate nuclides for prospective industrial gamma sources [10]. Concerning the penetration capability of gamma radiation the Europium radionuclides are quite comparable with conventional industrial radionuclides ^{60}Co and ^{137}Cs [11]. Unlike for X-ray and EB irradiation the broad isotropic gamma beam was simulated that is closer to the actual angular distribution of radiation of typical gamma irradiators.

In course of *RaT* modeling the depth dependencies of energy fluxes of all sorts of primary and secondary particles and the absorbed dose deposition profiles were scored and normalized per one primary electron (or photon for γ-irradiation) incident onto the transversal plane unit area per unit of time. These data can be easily scaled to the absorbed dose rates at certain beam current density (or gamma source activity).

For heterogeneous modeling setups depth dependencies of fluxes and doses were scored separately for syringe barrels, needles and their air filled holes as well as for environmental air. For comparison the modeling of dose deposition in the homogenized effective medium also were carried out for all kinds of irradiation.

2. EFFECT OF THE PRODUCT LOADING PATTERN ON THE ABSORBED DOSE SPATIAL DISTRIBUTIONS

The dose absorbed inside the material of the polymeric syringe barrel is supposed to be representative and close to the readings of technological film dosimeters and dose indicators [1]. The modeling results obtained for barrel dose depth dependencies at different product loading patterns are depicted in Fig.3. In general they indicate that the product heterogeneity becomes crucial namely for direct electron beam irradiation.

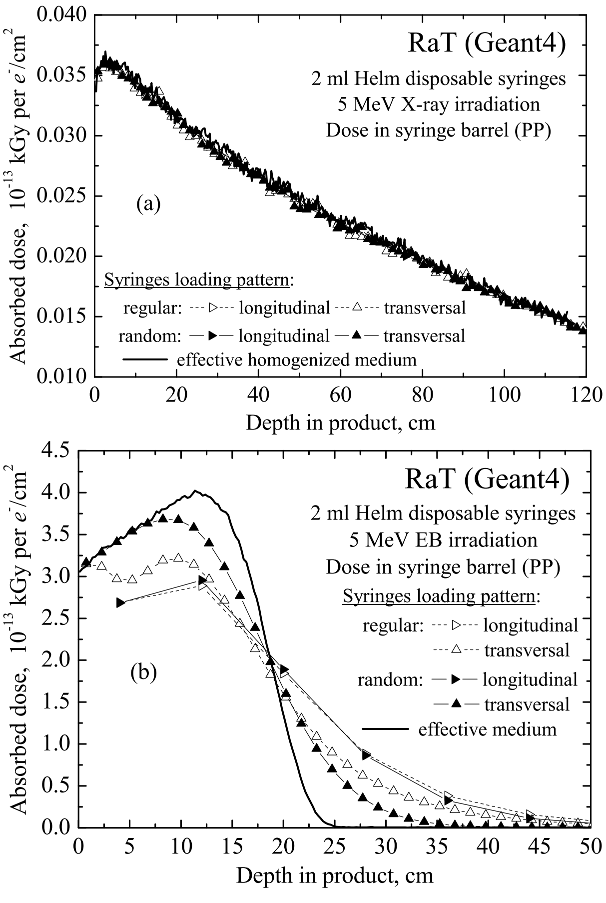

Fig.3. *Depth dependencies of absorbed dose in syringe barrels at X-ray (a) and EB (b) irradiation for different product loading patterns. Solid curves represent the modeling results obtained in the approximation of effective homogenized medium*

For X-ray irradiation (see Fig.3,a) the dose profiles are practically independent of the type and orientation of the product loading pattern and in particular of its regularity or stochasticity. All curves coincide with the depth-dose curve for effective homogenized medium. Similar behavior has been found for γ-irradiation having harder spectrum and larger penetrating capability.

On the contrary for EB irradiation the depth-dose curves in heterogeneous product substantially differ from those in the effectively homogenized medium (see Fig.3,b). One can see that the homogenization of medium results in considerable underestimation of the effective range of electrons down to $\sim$25 cm as compared to 35−50 cm for heterogeneous media. As a result all dose profiles in heterogeneous media demonstrate overextended tails spread to large depths.

However we expect these tails to have somewhat different nature in the cases of regular and randomized loading patterns. Namely for the former case the directional effects of regular lattices transparency dominates that leads to enhanced transmission through aligned voids between syringes (a kind of particle "channeling") and to the growth of energy deposition at large depths. On the other hand for loading patterns randomized on a layer-by-layer basis the probability to find transparent voids is suppressed and the large-depth dose enhancement effect is of complex stochastic nature. Qualitatively similar effect of the stochastic blooming of random media (as compare to the averaged homogeneous medium) had been found in computer experiments concerning gamma irradiation of one-dimensional random layered structures and studied analytically in Ref. [9].

Among intrinsic heterogeneity effects at EB irradiation one should also distinguish the directional effects of the product unit orientation and the effects of loading pattern randomization.

The effect of syringes orientation is considerable for all kinds of loading patterns but changes its sign as the penetration depth increases. For small depths transversal loading patterns demonstrate higher dose deposition then the longitudinal patterns. At large depths the effect is completely adverse.

The dose profile for the regular transversal loading pattern demonstrates the unforeseen feature, the minimum at small depth $z \approx 5$ cm, that is absent for homogenized medium and randomized patterns. This feature is not peculiar for conventional unimodal profiles of EB dose deposition in homogeneous media. To clarify its nature the depth profiles of the electron energy fluxes are shown in Fig. 4.

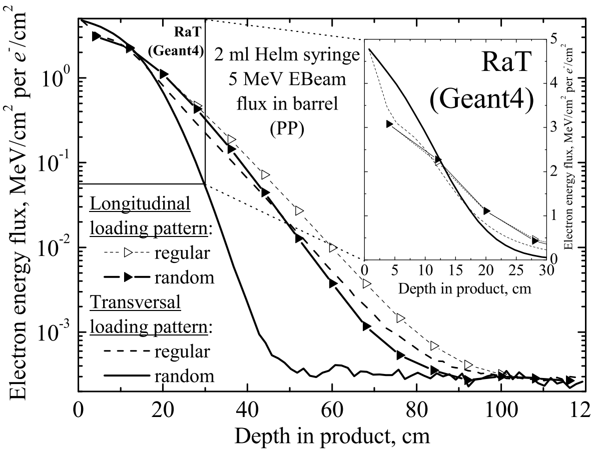

Fig.4. *Depth dependencies of the particle energy fluxes in syringe barrels for different loading patterns under EB irradiation. The inset plot illustrates the small-depth behavior of the same curves*

It is clear from the Fig.4 inset plot that near the outer surface of the lattice of transversally arranged syringes the enhanced stopping of initially parallel electron beam takes place and a kind of particle flux blocking occurs. Consequently the surface peak of energy deposition is observed in Fig.3,b at depths less then the CSDA range in polypropylene (its value at surface is close to the value for the homogenized medium). It is due to the electrons stopped in the near-surface layers.

However certain beam fraction reaches larger depths through open channels and gradually experiences lateral scattering. At $z > 5$ cm the beam angular spreading becomes the dominating factor that forms the peak at $z \approx 10$ cm, the same depth where the energy deposition maximum is located for randomized transversal loading pattern that prohibits the long-range directional effects.

At the depth-dose dependencies of Fig.3,b no appreciable effects of syringe layers randomization are observed for the longitudinal pattern while for the transversal patterns the presence of stochastic effect is evident and results in the smallest effective range of electrons among all versions of heterogeneous media.

It is explained by the reason that, similarly to the amplitude of the stochastic blooming effect [9], the amplitude of the randomization effects has to increase with the increase of the number N of the fluctuating layers (for our model of independent randomly shifted layers it is expected to be roughly proportional to $\sqrt{N}$).

For longitudinal orientation the unit of depth contains about fourfold smaller number of layers then that for the transversal one. Hence in the former case the randomization effects really have not time to become apparent at depths where the energy deposition is significant.

It is confirmed by the Fig.4 flux data where at $z > 40$ cm in the longitudinal patterns stochastic effects also begin to perturb the flux profiles; but the dose at such depths is marginal.

On the other hand for the transversal randomized loading pattern the stochastic enhancement of electron stopping and scattering leads to the complete elimination of primary beam electrons at $z > 50$ cm where the electron energy flux practically is not depth dependent. It is formed by Compton electrons produced by weakly absorbed bremsstrahlung photons. For regular patterns and for longitudinal randomized pattern similar effect is observed at doubled depth of about 1 m.

In general one can conclude that due to the combination of heterogeneity and stochasticity of EB irradiated medium the uniformity of absorbed dose delivery across the depth in irradiated product is improved as compared with the homogeneous medium of effective density and composition. The modeling also allows to expect the longitudinal loading patterns to be more stable with respect to the effects of random variations of product units loading in packaging boxes.

3. DOSES IN VARIOUS COMPONENT PARTS OF IRRADIATED SYRINGES

Other valuable effects of the irradiated product heterogeneity concern the differences of absorbed dose values in different component parts of the product unit. They can be of great importance for the optimization of irradiation processes and the evaluation of achievement of irradiation goals (e.g. sterilization). In general these effects are hard to estimate in the homogenized medium approximation and to measure experimentally.

Results of modeling of depth-dose dependencies in various component parts of syringes for different kinds of irradiation are illustrated by Figs.5 and 6.

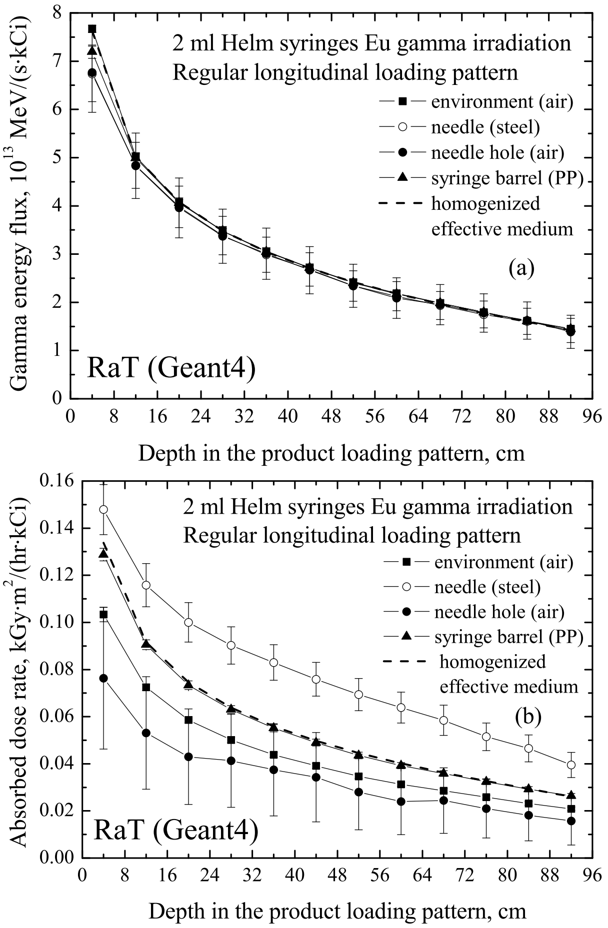

Fig.5. *Depth dependencies of the gamma quanta energy fluxes (a) and absorbed doses (b) in various component parts of syringes for regular longitudinal product loading pattern irradiated by γ-radiation of a mix of Europium radionuclides. Dashed curves represent the profiles in the effective homogenized medium*

Concerning the gamma irradiation one should note that the product unit heterogeneity only weakly perturbs the energy flux I_E of hard gamma quanta (see Fig.5,a).

Supposing that the electronic equilibrium is reached in the bulk of product layer the absorbed dose D is close to photon kerma K and can be calculated by the formula:

$$D \approx K \propto \int_{E_\gamma} \frac{\mu_{en}(E_\gamma)}{\rho} \cdot I_E(E_\gamma) dE_\gamma, \qquad (1)$$

where (μ_{en}/ρ) is the mass-energy absorption coefficient at photon energy E_γ and the unessential dimensional factor is omitted.

Since $I_E(E_\gamma)$ is practically common to all syringe components the differences of absorbed doses in different component parts are mainly determined by the differences in μ_{en}/ρ for different materials. The doses are maximal in the heavy material of the syringe needle. The dose in the polymeric barrel is representative as compared with the averaged dose in effective medium. The dose in the needle hole is minimal even in comparison with the dose averaged over the environmental air; this is due to the holes shielding by the steel body of needles.

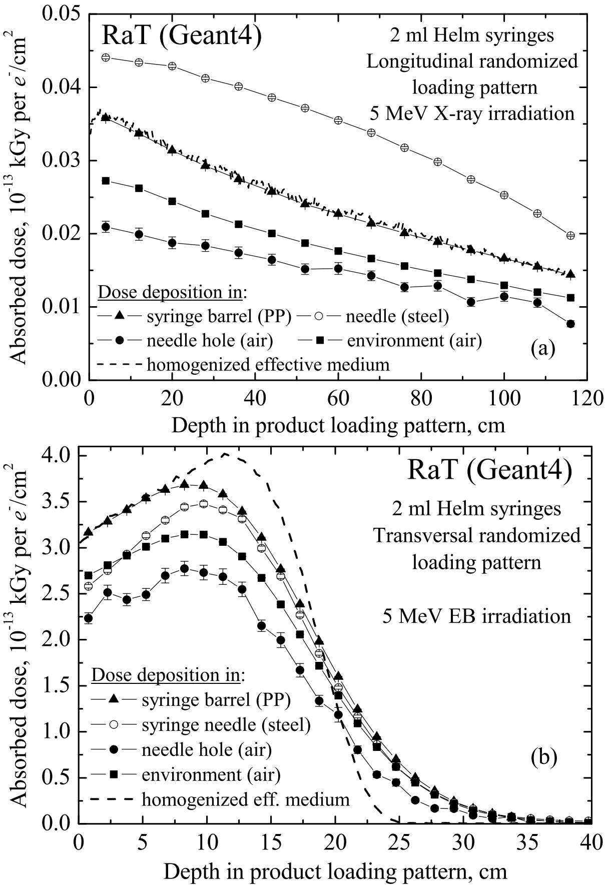

Fig.6. *Depth dependencies of absorbed doses in various component parts of syringes for randomized transversal product loading pattern at X-ray (a) and EB (b) irradiation. Dashed curves represent the profiles in the effective homogenized medium*

Exactly the same interrelation of doses absorbed in different component parts is observed for softer X-ray beam (see Fig.6,a) though the shapes of depth-dose curves are different for another kind of beam (mainly due to different initial angular distribution of photons).

For EB irradiation (see Fig.6,b) right up to the effective range of electrons the dose in the syringe barrel dominates over doses in other component parts and particularly in the needle (the latter is opposite to the cases of X-ray and gamma irradiation). The dose absorbed in the needle hole is again the smallest one. One should note that at large $z > 30$ cm the interrelation between the component parts doses becomes similar to that observed for photon irradiation; this is due to the contribution of electron bremsstrahlung.

The decontamination of internal surfaces of syringe needles is the critical moment of the process of radiation sterilization of this medical item. Since it is hard to apply the experimental dosimetry methods for measurements inside the needle hole the modeling provides a unique tool to clarify the dose accumulation within the needle. This problem is hard for Monte Carlo modeling too because it requires the achievement of good statistics of energy deposition events inside small 3D objects.

For EB irradiation we have studied in detail the interrelation of the mean doses absorbed in the needle material and in the air inside the hole. In Fig.7 the "needle-to-hole" dose ratios are plotted as functions of depth for different orientations of syringes in a loading pattern.

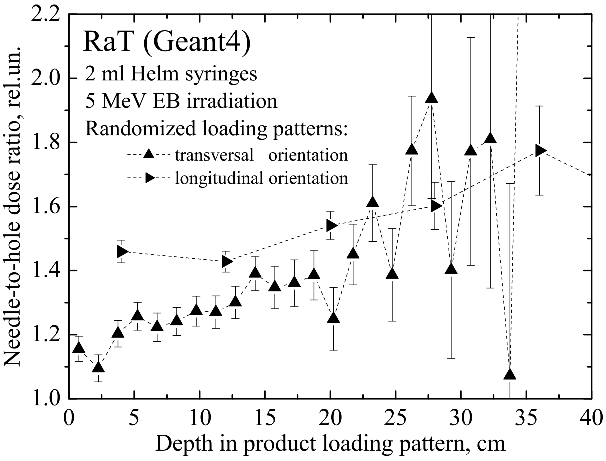

Fig.7. *Depth dependencies of the ratio of mean doses absorbed in the needle material and in the air-filled needle hole for different product loading patterns*

One can see from Fig.7 that at depths $z < 25$ cm where dose rates are significant the transversal loading pattern in which needles are directed orthogonally to the beam axis provides better uniformity of dose fields inside needles and holes. At deeper z both ratios grow.

Even finer computer experiment has been carried out for gamma irradiation. Namely the radial distribution of absorbed dose and photon kerma has been calculated inside the syringe needle with radial resolution of 10 μm. For this calculation the solitary syringe model embedded into the homogenized medium to take into account scattered photons and secondary particles was irradiated isotropically by γ-radiation of the mixture of Europium radionuclides. The modeling results are shown in Fig.8.

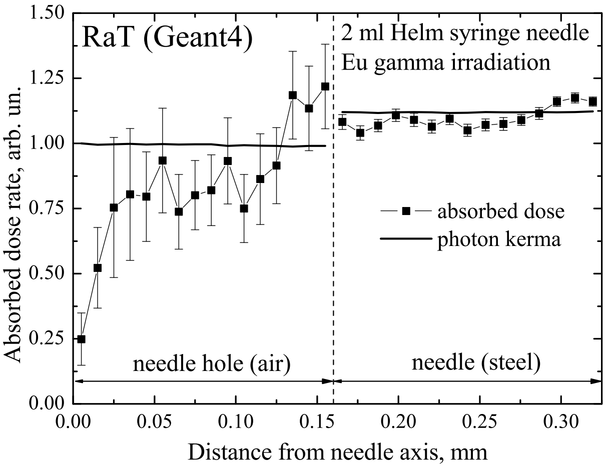

Fig.8. *Fine structure of the distribution of photon kerma and absorbed dose over the syringe needle radius for the syringe embedded into the homogenized product medium irradiated by the isotropic gamma radiation of Europium radionuclides*

One can see that inside the needle material the absorbed dose is close to photon kerma; hence for steel the electronic equilibrium is reached. Inside the needle hole the kerma is constant due to the constancy of photon flux in air. On the contrary the absorbed dose has strong radial variation that is completely due to the non-equilibrium effects in view of the proximity of dense material. The mean value of absorbed dose in the needle hole is 5% lower then the photon kerma level. However due to the surface buildup effect the dose in air near the surface is close to the average dose in the needle material.

Therefore one can conclude that the dose absorbed in the syringe needle material is representative from the point of view of the needle surface decontamination.

Guardedly extrapolating this conclusion onto the case of EB irradiation one should notice that in this case the estimation of the achievement of decontamination dose using the dose absorbed in the polymeric components of syringes can result in certain underirradiation of the needle surfaces (see Fig.6,b). For gamma and X-ray irradiation this estimation is conservative because the dose in a syringe barrel is the highest one.

4. CALCULATIONS OF PARAMETERS OF IRRADIATION PROCESSES

Indispensable standard parameters of irradiation pro-cesses are the regulated minimal absorbed dose D_{min} in a product that is required to achieve the desired irradiation effect (e.g. the product sterilization; for this purpose typically $D_{min} = 25$ kGy) and the lowest achievable dose uniformity ratio (DUR) $\delta = D_{max}/D_{min}$ where D_{max} is the maximal dose absorbed in the irradiated product stack.

To improve the dose field uniformity the two-sided irradiation from the opposite directions is commonly applied till equal dose values are delivered by each side irradiation. In this case the total dose D_2 a tance z from the edge of the product stack of t ness L is a sum of one-side irradiation depth- curves $D_1(z)$:

$$D_2(z; L) = D_1(z) + D_1(L - z).$$

It has been shown in Ref. [11] that for any cific value of the DUR δ the maximal allowed pro thickness $L_{max}(\delta)$ of the product stack is determ by the maximal root of the non-linear equation:

$$\max\{D_2(z; L_{max})\} = \delta \times \min\{D_2(z; L_{max})\},$$

where the search of maximum and minimum is ried out upon the variable z. It can be accompli using the depth-dose dependencies $D_1(z)$ obtained by the computer simulation methods. We have performed such a procedure for all kinds of irradiation using the dose profiles obtained for syringe barrels.

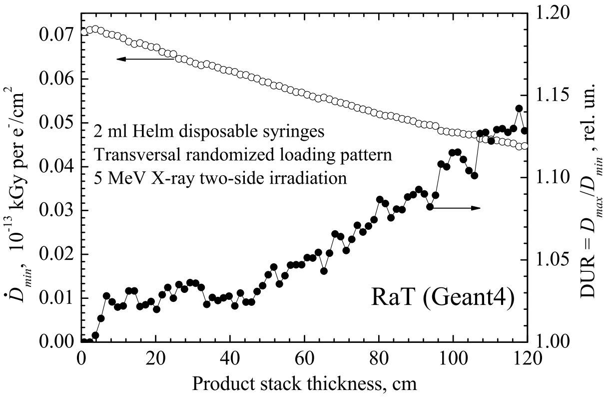

Fig.9. *The dependencies of the minimal dose rate $\dot{D}_{min}$ and the dose uniformity ratio on the product stack thickness for two-sided X-ray irradiation*

As it can be seen from Fig.9 for X-ray irradiation the minimal absorbed dose rate $\dot{D}_{min}$ gradually decreases with L except for the thin surface buildup layer. For this case the function $\delta(L)$ is monotone increasing and the equation (3) has only one root. The very acceptable values of DUR $\delta < 1.15$ are achieved at all values of product stack thickness $L < 1.2$ m considered in our modeling. Therefore at X-ray irradiation (as well as at irradiation by harder gamma quanta) of such a low-density medium the issues of dose uniformity can arise only at much greater product thickness.

The case of EB irradiation is much more complex due to smaller ranges of electrons and non-monotonic profiles of absorbed dose. In Fig.10 dose profiles derived from Eq. (2) for two-sided EB irradiation at increasing syringe layer thickness L are shown.

One can see that the shape of profile changes qualitatively as L increases. At small L the maximum is located in the layer symmetry plane. At greater L it splits into two separated maxima while a broad minimum appears near the symmetry plane. Other local minima are observed at layer surfaces. Such a multimodal behavior complicates the solving of Eq. (3) that can have multiple roots. The best way is to perform it graphically.

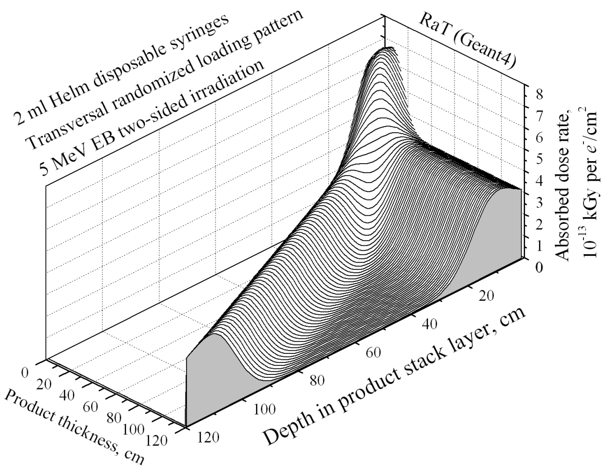

Fig.10. *Symmetric depth profiles of absorbed dose in syringe barrels at two-sided EB irradiation of product layers of different thickness*

The results of quantitative analysis are illustrated by Fig.11. It is clear that at large L the DUR rapidly grows to inadmissible large values. Obviously DUR is good for thin layers ($L < 10$ cm) but they are unacceptable on the subject of the irradiation process throughput capacity.

The optimal thickness corresponds to the sharp minimum of the dependency $\delta(L)$. For all product loading patterns it is located at thickness $L_{max} \approx 40 - 45$ cm that is close to the thickness of one eurobox. One can notice that it slightly greater then the doubled characteristic depth R_{50} for EB dose deposition profile in the effective homogenized medium (see Fig.3,b; R_{50} is the depth where the dose on the decaying part of the profile equals to the half of maximal dose). The optimal thickness is characterized by the definite value of minimal dose rate that in general decreases as L increases.

Further comparative analysis of Fig.11,a,b shows that the optimal value $\delta \approx 1.2$ is practically independent on the kind of the product loading pattern. The application of the homogenized medium approximation (see Fig.11,c) results in greater optimal dose uniformity ratio $\delta = 1.32$ that is overestimated by 8%.

At longitudinal product orientation the optimal DUR value is reached at somewhat greater (by 4−5 cm) thickness that allows irradiating of larger amount of syringes in a container. However it has to be noticed that the corresponding minimal dose rate $\dot{D}_{min}(L_{max})$ is 15% higher at the transversal orientation of syringes. It is a competitive factor that controls the speed of the desired dose delivery and in conjunction with the product amount irradiated per unit of time determines the throughput capacity P of a process under optimization.

This integral quantity can be estimated as follows (we omit the factor inessential for comparative analysis):

$$P(L) \propto \frac{\dot{D}_{min}(L)}{D_{min}} \cdot L. \qquad (4)$$

Far from the optimal product stack thickness the functions $P(L)$ shown in Fig.12 substantially depend on the product loading pattern and drastically differ from the prediction of homogenized medium model.

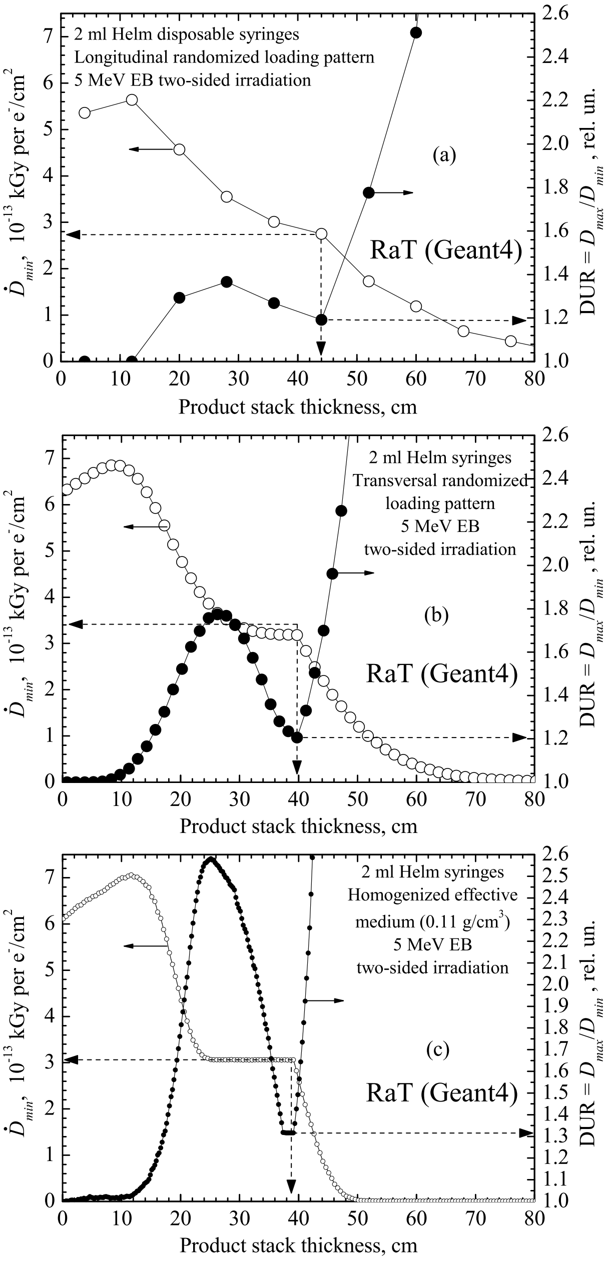

Fig.11. *The L-dependencies of* $\dot{D}_{min}$ *and DUR for two-sided EB irradiation of different loading patterns of syringes (a,b) and the homogenized medium (c)*

Near the optimal thickness $L_{max} \approx 40$ cm the P-curves differ only quantitatively and have close optimal values for all kinds of product loading patterns. It means that $L = L_{max}$ corresponds to the case when practically the whole electron beam energy contributes to the dose deposition irrespective of the details of the dose profile.

However the highest throughput capacity at optimal thickness is observed for the transversal randomized loading pattern. The value derived from the homogenized medium approximation is about 6% lower. Thus the arrangement of syringes under irradiation opens the possibility to optimize the process productivity that is especially important for large-scale contract irradiators.

One can conclude that using advanced technique of Monte Carlo modeling of energy deposition in complex heterogeneous media we have demonstrated the complete cycle of calculations of technological parameters of the process of radiation sterilization of medical items at electron beam, X-ray and gamma irradiation. The capabilities of the *RaT* code allow to perform such calculations for arbitrary sorts of irradiated products taking into account their complex geometry and composition.

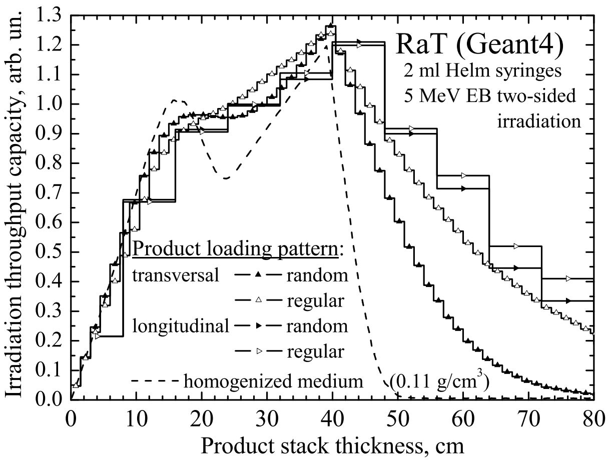

Fig.12. *The L-dependencies of the normalized throughput capacity P of two-sided EB irradiation process for different loading patterns of syringes and for the effective homogenized medium*

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ВЛИЯНИЕ ГЕТЕРОГЕННОСТИ ОБЪЕКТОВ ОБРАБОТКИ ПРОМЫШЛЕННЫХ РАДИАЦИОННЫХ ТЕХНОЛОГИЙ НА ПРОСТРАНСТВЕННЫЕ РАСПРЕДЕЛЕНИЯ ПОГЛОЩЕННЫХ ДОЗ ПРИ ЭЛЕКТРОННОМ, РЕНТГЕНОВСКОМ И ГАММА-ОБЛУЧЕНИИ

С.В. Дюльдя, М.И. Братченко

Путем моделирования методом Монте-Карло изучено влияние гетерогенности и пространственного размещения облучаемых одноразовых шприцов на профили поглощенной дозы при различных видах облучения. Для электронного облучения обнаружены существенные отклонения от предсказаний обычного приближения гомогенизированной среды. Выявлены зависимости технологических параметров облучения от ориентации и регулярности/стохастичности расположения шприцов под облучением, различия в накоплении дозы в различных деталях шприца и неравновесные дозовые эффекты на внутренней поверхности его иглы.

ВПЛИВ ГЕТЕРОГЕННОСТІ ОБ'ЄКТІВ ОБРОБКИ ПРОМИСЛОВИХ РАДІАЦІЙНИХ ТЕХНОЛОГІЙ НА ПРОСТОРОВІ РОЗПОДІЛИ ПОГЛИНЕНИХ ДОЗ ЗА УМОВ ЕЛЕКТРОННОГО, РЕНТГЕНІВСЬКОГО ТА ГАММА-ОПРОМІНЮВАННЯ

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Шляхом моделювання методом Монте-Карло вивчено вплив гетерогенності та просторового розташування одноразових шприців під опроміненням на профілі поглиненої дози за різних видів опромінення. Для електронного опромінювання знайдені суттєві відхилення від передбачень звичайного наближення гомогенізованого середовища. Виявлені залежності технологічних параметрів опромінювання від орієнтації та регулярності/стохастичності розташування шприців під опроміненням, різниці в накопиченні дози у різних деталях шприцу та нерівноважні дозові ефекти на внутрішній поверхні його голки.