

Geant4 Simulation of Radiation-Induced Dose in Keratinocyte Cell Organelles and Membranes

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ABSTRACT

Background: Accurate modeling of radiation-induced damage at the subcellular level is essential for advancing radiobiological research and therapeutic outcomes.

Objective: This study used Geant4 Monte Carlo simulations to quantify energy deposition and dose distribution in keratinocyte cell nuclei, mitochondria, and lysosome membranes exposed to electron, proton, and alpha radiation. The goal is to elucidate subcellular damage mechanisms and enhance radiobiological models.

Material and Methods: In this computational Monte Carlo simulation study, Geant4 is used to model a realistic 3D human keratinocyte carcinoma cell, including its nucleus, lysosome, and mitochondrion. The simulation was conducted for electron, proton, and alpha particles across 0.02–100 MeV energy levels. The absorbed energy and dose were calculated for each organelle and cellular membrane.

Results: Membranes absorbed significantly higher doses than cytoplasm and organelles, with the nucleus receiving the highest dose among organelles. Notably, alpha particles resulted in absorbed doses four times higher than protons at the same energy across the entire cell. The higher hydrogen content in membranes contributed to increased energy deposition, making them a potential indirect radiation target.

Conclusion: This in silico study highlights that cell membranes absorb more radiation than organelles, which could lead to radiation-induced cell damage at lower doses. The findings provide valuable insights into the role of material composition in dose absorption and demonstrate a methodology for simulating complex intracellular structures, for a better understanding of radiation effects at the microscopic level.

Keywords

Monte Carlo Method; Radiobiology; Keratinocytes; Radiation Dose; Cell Membrane; Cell Nucleus; Mitochondria; Lysosomes

Introduction

The effects of radiation-induced damage at cellular and subcellular levels is crucial for advancing radiobiology, cancer therapy, and radiation protection. Ionizing radiation interacts with biological matter through direct and indirect mechanisms. Direct effects break covalent molecular bonds, while indirect effects produce highly reactive free radicals that damage Deoxyribonucleic Acid (DNA), proteins, and lipid membranes [1, 2]. Extensive radiation damage can lead to apoptosis or necrosis, whereas sub-lethal damage may activate repair pathways

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or cause mutagenesis, potentially resulting in long-term biological consequences [1, 2].

Although nuclear DNA damage has been extensively studied, the role of organelles and intracellular membranes in radiation-induced effects remains underexplored [3, 4]. Mitochondria and lysosomes are particularly vulnerable to radiation exposure due to their functional significance in cellular metabolism and degradation pathways [5, 6]. Mitochondrial damage can lead to Adenosine Triphosphate (ATP) depletion, increased Reactive Oxygen Species (ROS) production, and apoptosis [7]. Likewise, lysosomal damage can cause the release of hydrolytic enzymes, leading to intracellular degradation and inflammatory responses [8-10]. Moreover, cellular and organelle membranes, which regulate intracellular transport and signaling, can be significant radiation targets, influencing cellular viability [11].

Monte Carlo (MC) simulations have become an indispensable tool for understanding radiation interactions at the microscopic scale, offering detailed modeling of energy deposition and dose distributions in biological structures [12]. The Geant4 Monte Carlo toolkit, specifically its Geant4-DNA extension, has enabled researchers to model cellular radiation response with high spatial resolution, allowing for simulations of realistic subcellular structures, including cytoplasm, organelles, and membranes [13]. While previous studies have focused on estimating absorbed dose within nuclei [3, 11], many of the previous studies relied on simplified cell models that assume a homogeneous water-based composition rather than realistic intracellular structures [14, 15].

Keratinocytes serve as a primary defense layer against environmental radiation exposure, which were frequently studied in radiation-induced skin damage and cancer research [16]. While several studies have examined electron, proton, and alpha particle interactions with keratinocyte cells, little attention has been given to the role of intracellular

membranes and their material composition in radiation dose absorption [12, 17]. Given that, membranes contain higher hydrogen content than other cellular components, their interaction with radiation differs from that of organelles, leading to potentially underestimated radiation-induced damage effects [18].

This study presents a realistic keratinocyte cell model with distinct nuclear, mitochondrial, lysosomal, cytoplasmic, and membrane compartments to investigate radiation-induced dose distribution across these subcellular structures. Using Geant4 Monte Carlo simulations, we analyze the energy deposition patterns of electrons, protons, and alpha particles across different cellular regions. Unlike previous models [1, 2, 4, 6, 12, 14, 15], this study incorporates a more accurate chemical composition of each organelle and membrane, providing a comprehensive evaluation of how subcellular structures respond to radiation exposure. By quantifying absorbed dose distribution within these compartments, this study aimed to enhance our understanding of radiation-induced cellular damage beyond nuclear DNA effects and contribute to the development of improved radiobiological models and radiation therapy strategies.

Material and Methods

A computational Monte Carlo simulation was conducted using Geant4 (version 10.4) (Geant4) to investigate radiation-induced dose distribution in a detailed model of a human keratinocyte cell. The cell was modeled as a sphere with a radius of 5 μm , containing a nucleus (radius 2 μm), mitochondria, lysosomes, and their respective membranes. The sizes of organelles and the thicknesses of their membranes were based on values from the literature. Lysosomes were modeled as spheres with a radius of 520 nm [19], while mitochondria were modeled as ellipsoids with radii of 450 nm, 250 nm, and 150 nm [19]. Membrane thicknesses were 5 nm for lysosomes, 87 nm for the nucleus, and 74 nm for mitochondria

[1, 14, 20]. Quasi-realistic chemical compositions were assigned to each cellular compartment (cytoplasm, nucleus, mitochondria, lysosome, cell membrane, and organelle membranes), as detailed in Table 1, with a uniform density of 1.0 g/cm^3 assumed for all materials, consistent with standard practices in Monte Carlo simulations for biological tissues.

The simulation included three types of primary particles: electrons, protons, and alpha particles. Electrons were simulated across energies from 0.02 to 100 MeV, protons from 0.5 to 100 MeV, and alpha particles at a fixed energy of 2 MeV to assess their high Linear Energy Transfer (LET) effects. For each particle type and energy level, 10^6 primary particles were simulated, with the particle beam propagation axis aligned parallel to the z-axis to ensure consistent interaction geometry.

To accurately model radiation interactions across the energy spectrum, two physics lists were employed, as follows: 1) the Geant4-DNA physics model (Geant4-DNA) was used for low-energy interactions (below 1 keV). This model is specifically designed for nanoscale simulations in biological systems, enabling precise tracking of particle interactions in thin structures such as cell membranes (5–10 nm thick). 2) The Livermore physics list was utilized for electromagnetic processes at higher energies, complementing the Geant4-DNA model to ensure comprehensive simulation of energy deposition across all energy ranges.

To balance computational efficiency and

accuracy, a cut-off energy of 1 keV was implemented for secondary particle production. Secondary particles with energies below 1 keV were not tracked, as their contribution to dose deposition in cellular compartments was considered minimal. A step size limiter of 10 nm was applied to align the simulation step length with the thickness of cellular membranes, ensuring precise tracking of particle interactions in these critical regions. While this setup provided accurate primary dose estimations, the impact of secondary electrons (delta rays) with energies below the cut-off threshold was not fully explored, representing a limitation to be addressed in future studies.

Energy deposition was recorded for each cellular compartment (cytoplasm, nucleus, mitochondria, lysosome, cell membrane, and organelle membranes). The absorbed dose was calculated by dividing the total energy deposition by the mass of each compartment, using the assumed density of 1.0 g/cm^3 . Statistical uncertainty in the dose calculations, estimated from the standard deviation of the mean dose across the 10^6 simulated events per energy point, was less than 1%, indicating high precision in the results.

This simulation setup enabled a detailed analysis of radiation-induced dose distribution at the subcellular level, providing insights into the differential effects of various radiation types and energies on keratinocyte cell components.

For the first time, we are simulating a cell's chemical composition, membrane, and

Table 1: Chemical compositions of membranes, cytoplasm, nucleus, lysosome and mitochondria

	H	O	C	N	P	Na	S	Cl	K	Ca
Membranes	44.4	22.2	11.2	22.2	0	0	0	0	0	0
Cytoplasm	10.55	56.30	29.88	2.51	0.04	0.11	0.24	0.16	0.21	0
Nucleus	10.60	74.20	9.00	3.20	2.60	0	0.40	0	0	0
Lysosome	7.38	65.81	17.76	5.10	0.62	1.24	0	1.36	0.19	0.0008
Mitochondria	7.38	65.81	17.76	5.10	0.62	1.24	0	1.36	0.19	0.0008

component membrane. These scales are microscopic and nanometric; accordingly, they are acceptable to use the entire complex volume as a sensitive site.

Figure 1 illustrates the subcellular compartments of a keratinocyte cell, including the nucleus, mitochondria, lysosomes, cytosol, and cell membrane, which were modeled to assess radiation-induced dose distribution.

Results

Absorbed Dose Distribution for Proton Irradiation

A proton beam with energies of 0.5, 1, 2, 5, 10, 20, 50, and 100 MeV was simulated.

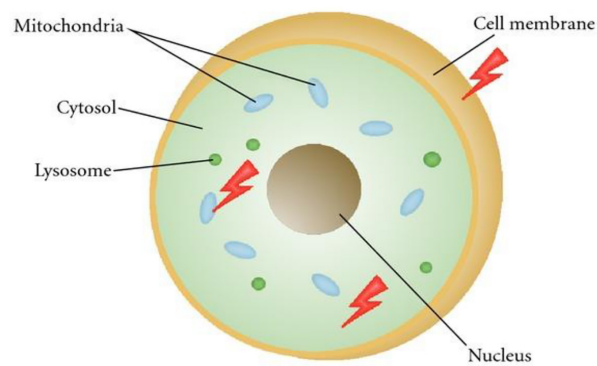


Figure 1: Schematic representation of the simulated cellular model used in this study.

Figure 2 shows the absorbed dose in various cellular compartments as a function of proton energy. Membranes absorb significantly higher doses than cytoplasmic and organelle compartments, with the nucleus receiving the highest dose among organelles. At 0.5 MeV, the cytoplasmic dose is lower than in organelles, while the cell membrane dose is notably less than that in organelle membranes.

Absorbed Dose Distribution for Alpha Particle Irradiation

Figure 3 presents the absorbed dose in cellular compartments for 2 MeV alpha particle irradiation. Organelle membranes exhibit higher doses than the cytoplasm and other organelles, with the total cellular dose being four times higher than that from protons at the same energy. The LET of alpha particles, approximately 10 times higher than protons, results in more localized energy deposition.

Absorbed Dose Distribution for Electron Irradiation

Electron irradiation was simulated at energies of 0.02, 0.05, 0.1, 0.2, 0.5, 1, 2, 5, 10, 20, 50, and 100 MeV. Figure 4 shows that membranes receive significantly higher doses than cytoplasm and organelles, with elevated doses persisting as electron energy increases,

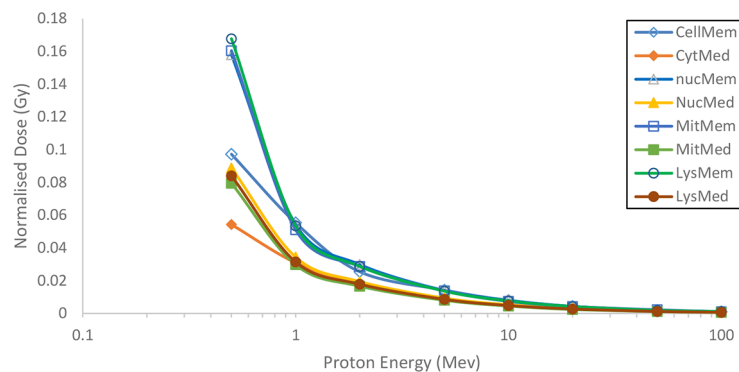


Figure 2: Absorbed dose (averaged over 10^6 proton events) as a function of proton energy in cell membrane (CellMem), cytoplasmic material (CytMed), nucleic membrane (NucMem), nucleus material (NucMed), mitochondria membrane (MitMem), mitochondrial inner material (MitMed), lysosome membrane (LysMem), and lysosome inner material (LysMed).

indicating enhanced ionization effects in these regions.

Comparison of LET and Absorbed Dose

Figure 5 provides an analysis of the absorbed energy and dose as a function of LET for electrons, protons, and alpha particles. LET (20–130 keV/ μm) yields approximately 10 times higher membrane dose than high-energy electrons. For proton beams (LET 300–4000 keV/ μm), the absorbed dose is 20 times higher, while alpha radiation (LET 5000–16000 keV/ μm) results in a 4-fold increase in absorbed dose compared to protons.

Discussion

The shift beyond DNA-centric dosimetry: Historically, the prevailing paradigm of radiation biology has focused almost exclusively on energy deposition within the cell nucleus, assuming nuclear DNA damage is the sole driver of biological outcomes [4, 6, 10, 12]. However, our results align with a paradigm shift recognizing the whole cell as a radiation sensor, providing physical evidence that extra-nuclear targets, specifically the cytoplasm and its organelles, are critical for initiating radiation responses [4, 5, 12, 17, 21]. Our finding that sub-cellular membranes receive significant localized doses is consistent with the

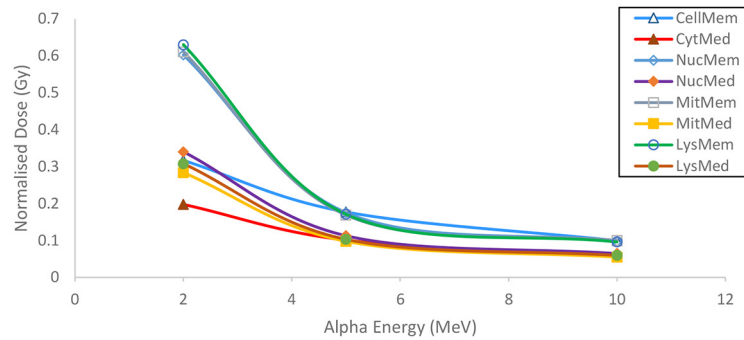


Figure 3: Absorbed dose (averaged over 10^6 proton events) as a function of proton energy in cell membrane (CellMem), cytoplasmic material (CytMed), nucleic membrane (NucMem), nucleus material (NucMed), mitochondria membrane (MitMem), mitochondrial inner material (MitMed), lysosome membrane (LysMem) and lysosome inner material (LysMed).

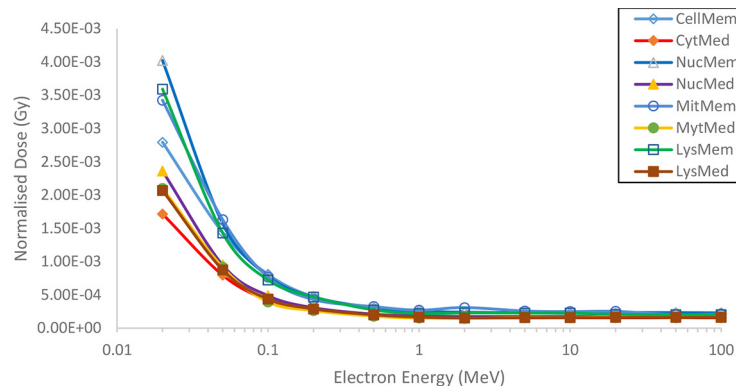


Figure 4: Absorbed dose (averaged over 10^6 proton events) as a function of proton energy in cell membrane (CellMem), cytoplasmic material (CytMed), nucleic membrane (NucMem), nucleus material (NucMed), mitochondria membrane (MitMem), mitochondrial inner material (MitMed), lysosome membrane (LysMem) and lysosome inner material (LysMed).

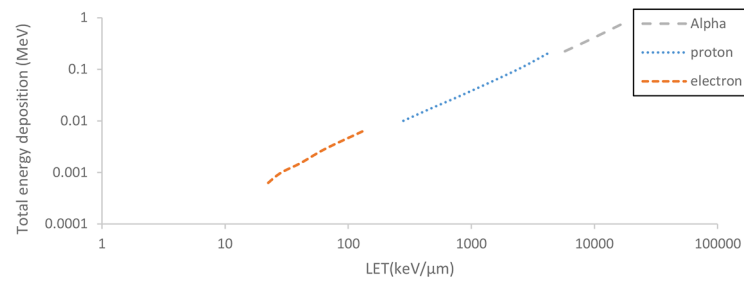


Figure 5: The total energy absorbed in the cell in terms of Linear Energy Transfer (LET) of electron, proton, and alpha particles.

view that structural membrane damage can act as a biosensor for oxidative stress and initiate cell death through signaling pathways [4, 10, 12, 17]. This extra nuclear sensitivity is particularly evident in high-LET scenarios, such as alpha-particle irradiation, where targeting the cytoplasm alone is sufficient to induce mutations and bystander effects [4, 6, 12, 17].

Geometry, morphology, and the voxelized phantom: A major strength of this study is the transition from simplified mathematical models to realistic 3D voxelized phantoms [9, 10, 19, 22]. Traditional analytical models often assume uniform geometries, yet our data confirms that energy deposition can vary significantly due to the irregular morphology encountered in real cell populations [10, 19, 20]. By utilizing high-resolution confocal microscopy of HaCaT cells, our simulation accounts for the irregular morphology of keratinocytes, which has been shown to have a stronger impact on energy deposition than imaging resolution itself [9, 12, 19]. This level of detail is essential for alpha-particle dosimetry, where the short range of the particles makes results highly sensitive to sub-cellular spatial distributions [1, 12, 19].

The influence of realistic chemical composition: Our simulations demonstrate that liquid water, a common surrogate for biological material, is insufficient to capture the full effect of radiation damage at the sub-cellular level [8, 17, 23]. Significant dose variations occur when applying quasi-realistic chemical

compositions, particularly at lower energies where the presence of elements like phosphorus and trace minerals alters ionization counts compared to a uniform water medium [4, 17, 20, 23]. Furthermore, our data indicates that hydrogen content is a primary driver of energy deposition discrepancies in membranes, emphasizing the need for precise elemental mapping in microdosimetry [4, 10, 12, 17, 19, 20, 23].

Organelles as critical targets, mitochondria and lysosomes: The elevated energy deposition observed in mitochondrial and lysosomal membranes carries profound biological implications [4, 22, 23]. Mitochondria are not only central to energy metabolism but are also key regulators of apoptosis; damage to these organelles can trigger the release of reactive oxygen species (ROS) and cytochrome c, initiating a cascade that leads to cell death even if the nucleus is spared [12, 17, 21, 23]. Similarly, the localized dose in lysosomal membranes provides a physical basis for non-targeted responses, as lysosomal rupture can release degradative enzymes that compromise cellular homeostasis [4].

Biological Consequences and Non-Targeted Effects: The calculated doses in keratinocyte membranes likely contribute to radiation-induced bystander effects (RIBE) and adaptive responses [5, 6, 12]. In skin tissue, where keratinocytes serve as an immune barrier, membrane damage can activate Toll-like receptors (TLRs), which contribute to innate immune

responses and inflammatory signaling [11]. Additionally, radiation-induced changes in membrane fluidity can disrupt transport properties and molecular signaling, potentially amplifying the effects of a single particle traversal to neighboring unirradiated cells [1, 4, 6, 10, 14].

Conclusion

This study successfully implemented a realistic 3D keratinocyte model in Geant4 to calculate radiation-induced doses in sub-cellular organelles and membranes. Our results demonstrate that sub-cellular morphology and chemical heterogeneity significantly alter energy deposition patterns, proving that liquid water models frequently underestimate doses to critical structures like mitochondrial membranes. We found that alpha-particle irradiation produces dense, localized ionizations capable of exceeding the thresholds for initiating ROS signaling and receptor-mediated apoptosis.

Furthermore, we conclude that the cytoplasm and its organelles are vital radiation targets that warrant investigation alongside nuclear DNA. The high doses received by cellular membranes suggest that non-targeted effects have a clear physical origin in extranuclear energy deposition. Future developments in Geant4-DNA will eventually allow for the explicit simulation of water radiolysis and free radical diffusion within these complex geometries, providing a complete bridge between physical energy deposition and observed biochemical damage. Ultimately, these findings contribute to a more comprehensive understanding of skin radiosensitivity and support the development of individualized dosimetry for clinical and environmental protection.

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presented remain the sole intellectual contribution of the authors. All AI-generated content was critically reviewed and revised to ensure accuracy and alignment with the intended message.

Authors' Contribution

H. Moradi conceptualized the study, designed the methodology, set up the simulations, analyzed the data, wrote and revised the manuscript, supervised the project, acquired funding, and approved the final manuscript. S. Faraji contributed to the conceptualization, simulation setup, data analysis, and manuscript writing. M. Shahaboddin handled the experimental data analysis, data processing, and statistical validation. B. Farhood, A. Aliasgharzadeh, and M. Mohseni contributed to the experimental data analysis, manuscript editing, and literature review. All authors have read and approved the final manuscript.

Ethical Approval

The Ethics Committee of Kashan University of Medical Sciences approved the protocol of the study (Ethic code: IR.KAUMS.NUHEPM.REC.1397.005).

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Conflict of Interest

None

References

1. Chouin N, Bernardeau K, Bardiès M, Faivre-Chauvet A, Bourgeois M, Apostolidis C, et al. Evidence of extranuclear cell sensitivity to alpha-particle radiation using a microdosimetric model. II. Application of the microdosimetric model to experimental results. *Radiat Res*. 2009;**171**(6):664-73. doi: 10.1667/RR1536.1. PubMed PMID: 19580473.
2. Chouin N, Bernardeau K, Davodeau F, Chérel M, Faivre-Chauvet A, Bourgeois M, et al. Evidence of extranuclear cell sensitivity to alpha-particle radiation using a microdosimetric model. I. Presentation and validation of a

- microdosimetric model. *Radiat Res.* 2009;**171**(6):657-63. doi: 10.1667/RR1371.1. PubMed PMID: 19580472.
3. Hamada N, Maeda M, Otsuka K, Tomita M. Signaling pathways underpinning the manifestations of ionizing radiation-induced bystander effects. *Curr Mol Pharmacol.* 2011;**4**(2):79-95. doi: 10.2174/1874467211104020079. PubMed PMID: 21143186.
 4. Kuncic Z, Byrne HL, McNamara AL, Guatelli S, Domanova W, Incerti S. In silico nanodosimetry: new insights into nontargeted biological responses to radiation. *Comput Math Methods Med.* 2012;**2012**:147252. doi: 10.1155/2012/147252. PubMed PMID: 22701142. PubMed PMCID: PMC3371690.
 5. Matsumoto H, Hamada N, Takahashi A, Kobayashi Y, Ohnishi T. Vanguard of paradigm shift in radiation biology: radiation-induced adaptive and bystander responses. *J Radiat Res.* 2007;**48**(2):97-106. doi: 10.1269/jrr.06090. PubMed PMID: 17327685.
 6. Morgan WF. Non-targeted and delayed effects of exposure to ionizing radiation: I. Radiation-induced genomic instability and bystander effects in vitro. *Radiat Res.* 2003;**159**(5):567-80. doi: 10.1667/0033-7587(2003)159[0567:nadeoe]2.0.co;2. PubMed PMID: 12710868.
 7. Morgan WF. Non-targeted and delayed effects of exposure to ionizing radiation: II. Radiation-induced genomic instability and bystander effects in vivo, clastogenic factors and transgenerational effects. *Radiat Res.* 2003;**159**(5):581-96. doi: 10.1667/0033-7587(2003)159[0581:nadeoe]2.0.co;2. PubMed PMID: 12710869.
 8. Incerti S, Douglass M, Penfold S, Guatelli S, Bezak E. Review of Geant4-DNA applications for micro and nanoscale simulations. *Phys Med.* 2016;**32**(10):1187-200. doi: 10.1016/j.ejmp.2016.09.007. PubMed PMID: 27659007.
 9. Incerti S, Seznec H, Simon M, Barberet P, Habchi C, Moretto P. Monte Carlo dosimetry for targeted irradiation of individual cells using a microbeam facility. *Radiat Prot Dosimetry.* 2009;**133**(1):2-11. doi: 10.1093/rpd/ncp003. PubMed PMID: 19174380.
 10. Oliver P. Computational cell dosimetry for cancer radiotherapy and diagnostic radiology [dissertation]. Ottawa: Carleton University; 2018.
 11. Köllisch G, Kalali BN, Voelcker V, Wallich R, Behrendt H, Ring J, et al. Various members of the Toll-like receptor family contribute to the innate immune response of human epidermal keratinocytes. *Immunology.* 2005;**114**(4):531-41. doi: 10.1111/j.1365-2567.2005.02122.x. PubMed PMID: 15804290. PubMed PMCID: PMC1782101.
 12. Byrne HL, Domanova W, McNamara AL, Incerti S, Kuncic Z. The cytoplasm as a radiation target: an in silico study of microbeam cell irradiation. *Phys Med Biol.* 2015;**60**(6):2325-37. doi: 10.1088/0031-9155/60/6/2325. PubMed PMID: 25715947.
 13. Alard JP, Bodez V, Tchirkov A, Nénot ML, Arnold J, Crespin S, et al. Simulation of neutron interactions at the single-cell level. *Radiat Res.* 2002;**158**(5):650-6. doi: 10.1667/0033-7587(2002)158[0650:soniat]2.0.co;2. PubMed PMID: 12385643.
 14. Garcia JJ, Martínez-Ballarín E, Millán-Plano S, Allué JL, Albendea C, Fuentes L, Escanero JF. Effects of trace elements on membrane fluidity. *J Trace Elem Med Biol.* 2005;**19**(1):19-22. doi: 10.1016/j.jtemb.2005.07.007. PubMed PMID: 16240667.
 15. Nelson DL, Cox MM. Lehninger Principles of Biochemistry. 7th Edition. New York: 2017.
 16. Le Grimmelc C, Friedlander G, el Yandouzi EH, Zlatkine P, Giocondi MC. Membrane fluidity and transport properties in epithelia. *Kidney Int.* 1992;**42**(4):825-36. doi: 10.1038/ki.1992.357. PubMed PMID: 1333546.
 17. Byrne HL, McNamara AL, Domanova W, Guatelli S, Kuncic Z. Radiation damage on sub-cellular scales: beyond DNA. *Phys Med Biol.* 2013;**58**(5):1251-67. doi: 10.1088/0031-9155/58/5/1251. PubMed PMID: 23380838.
 18. Reis JA, Bansal N, Qian J, Zhao W, Furdui CM. Effects of ionizing radiation on biological molecules--mechanisms of damage and emerging methods of detection. *Antioxid Redox Signal.* 2014;**21**(2):260-92. doi: 10.1089/ars.2013.5489. PubMed PMID: 24382094. PubMed PMCID: PMC4060780.
 19. Barberet P, Vianna F, Karamitros M, Brun T, Gordillo N, Moretto P, et al. Monte-Carlo dosimetry on a realistic cell monolayer geometry exposed to alpha particles. *Phys Med Biol.* 2012;**57**(8):2189-207. doi: 10.1088/0031-9155/57/8/2189. PubMed PMID: 22456322.
 20. Douglass M, Bezak E, Penfold S. Development of a randomized 3D cell model for Monte Carlo microdosimetry simulations. *Med Phys.* 2012;**39**(6):3509-19. doi: 10.1118/1.4719963. PubMed PMID: 22755731.
 21. McNamara AL, Ramos-Méndez J, Perl J, Held K, Dominguez N, Moreno E, et al. Geometrical structures for radiation biology research as implemented in the TOPAS-nBio toolkit. *Phys Med Biol.* 2018;**63**(17):175018. doi: 10.1088/1361-6560/aad8eb. PubMed PMID: 30088810. PubMed PMCID: PMC6176684.
 22. Zein S, Francis Z, Montarou G, Chandez F, Kane MS, Chevrollier A. Microdosimetry in 3D realistic mitochondria phantoms: Geant4 Monte Carlo tracking of 250keV photons in phantoms reconstructed from microscopic images. *Phys Med.* 2017;**42**:7-12. doi: 10.1016/j.ejmp.2017.08.005. PubMed PMID: 29173923.
 23. McNamara AL, Kam WWY, Scales N, McMahon SJ, Bennett JW, Byrne HL, et al. Dose enhancement effects to the nucleus and mitochondria from gold nanoparticles in the cytosol. *Phys Med Biol.* 2016;**61**(16):5993-6010. doi: 10.1088/0031-9155/61/16/5993. PubMed PMID: 27435339. PubMed PMCID: PMC4993038.