Modeling the Accumulation of Radiation Dose Over Time from a Decaying Radioactive Source and Its Implications for Health and Safety

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Abstract- This study investigates the accumulation of radiation dose over time in the presence of radioactive decay, analyzing the impact of half-life, initial dose rate, and decay constant on exposure levels. Using an analytical modeling approach, the research explores both short-term and long-term dose accumulation, highlighting key differences in radiation risk profiles. The findings indicate that sources with shorter half-lives cause rapid initial dose accumulation but stabilize quickly, whereas longer half-life sources contribute to prolonged radiation exposure. Sensitivity analysis reveals that variations in the initial dose rate significantly affect long-term exposure levels, while decay constants influence the rate at which radiation stabilizes. The study underscores the importance of managing these factors to minimize radiation risks **posesand** ***improve safety protocols in occupational and environmental settings. These insights are crucial for optimizing radiation protection strategies, ensuring controlled exposure, and mitigating long-term health effects.***

Indexed Terms- Decay constant, Half-life, Radiation dose accumulation, Radiation protection, Sensitivity analysis

I. INTRODUCTION

Radiation exposure is a serious issue for both medical and environmental purposes. Although background radiation from natural sources is always present, human exposure has increased dramatically due to manmade sources, especially in medical imaging [1, 2]. The accuracy of diagnosis and the effectiveness of treatment have been significantly improved by developments in radiography techniques, including computed tomography (CT), fluoroscopy, and interventional radiology. On the other hand, cumulative radiation exposure from repeated imaging raises questions regarding possible long-term health hazards. To reduce these concerns while preserving high-quality imaging and guaranteeing patient safety, effective dose management techniques are crucial [3, 4].

Understanding the accumulation of exposure over time is a crucial component of radiation safety. Radiation from a decaying radioactive source in physics decays exponentially, progressively reducing intensity as nuclear transformation takes place. However, exposure to medical radiation occurs sporadically and builds up over several imaging sessions, thus persistent monitoring is necessary to avoid overexposure [5]. The crucial question this is whether mathematical models that explain radioactive decay may be used to optimize radiation dose management in medical imaging. By using these models, it is possible to evaluate long-term radiation exposure and create plans to lower related hazards. In this work, we investigate the connection between radiation dose buildup from decaying radioactive sources and cumulative exposure in medical imaging. We forecast exposure concerns in medical imaging by analyzing the accumulation of radiation over time using dose modeling techniques. Our model measures dose buildup, analyzes the effect of exposure time, and evaluates important parameters including initial dose rate and decay properties. In order to maintain medical imaging's safety and efficacy in healthcare, this strategy offers a basis for strengthening monitoring systems, streamlining safety procedures, and strengthening regulatory frameworks.

II. REVIEW OF RELATED WORK

The accumulation of radiation doses is essential to the precision of treatment. The physiologically equivalent dose (bEQDd) model, which takes fractionation effects and tissue-specific reactions into consideration, was proposed by Niebuhr et al. [6]. The necessity of physiologically informed dose calculations was highlighted by their findings, which demonstrated that bEQDd exceeded conventional dose accumulation by 3.3– 4.9 Gy, reaching 8.4 Gy in hypofractionated regimens. Vassiliev [7] also studied sublethal radiation damage (SRD) and found that SRD buildup enhances radiosensitivity, causes a nonlinear-to-linear transition in survival curves, and begins below 1 Gy. These findings emphasize how crucial it is to combine biological and physical aspects in order to plan radiotherapy precisely. Additionally, Kuo et al. [8] used a radiotherapy dose accumulation routine (RADAR) to analyze the cumulative radiation dosage to organs at risk (OAR) for Glioblastoma Multiforme (GBM) cases. The potential for re-planning based on the cumulative doses to OARs and the significance of precise dose assessment in repeated treatment courses were highlighted by their discovery of notable dosage differences of up to 40 Gy between RADAR and manual calculations. Tangsiwong et al. [9] have looked into the cumulative radiation exposure of children having computed tomography (CT). According to their research, unique CT methods and scanner settings had a substantial impact on radiation exposure, even though the occurrence of high cumulative doses was minimal. Higher cumulative dosages were more frequently given to cancer patients, with some cases surpassing 300 mSv, they found.

The impact of alignment problems on dose accumulation in spatially fractionated radiation treatment (SFRT) was investigated by Ginn et al. [10]. Their study discovered that even little changes in patient placement resulted in a considerable smoothing of the high- and low-dose areas, which may have an effect on the efficacy of treatment. In the worst situation, there was a significant decrease in dosage contrast due to a 10 mm misalignment in two treatment portions. Radiation exposure and cancer risk were examined by Wong-Siegel et al. [11] in newborns with symptomatic tetralogy of Fallot (sTOF) undergoing primary repair (PR) or staged repair (SR). They discovered, using dosimetry methods, that radiation doses were considerably higher in SR patients (median: 8.3 mSv vs. 2.1 mSv, $P < 0.001$). Women were more likely to get cancer in their lifetimes, and the highest estimated risk (1.9/1,000) was found in breast tissue from SR patients. Female patients having SR had a 7.3% chance of thyroid cancer. The study emphasizes how radiation exposure in neonatal cardiac care must be kept to a minimum.

A study on radiation exposure among healthcare professionals using thermoluminescent dosimeters (TLDs) was carried out by Mohammed et al. [12]. According to their findings, radiologists received the lowest average radiation dosage (430 μGy), while radiographers received the highest (668.0 μGy). The maximum documented effective dosage was 7.44 mSv annually, which was still under the 20 mSv annual limit advised by the ICRP. Furthermore, radiologists had the lowest mean skin dose (0.09 mGy), whereas cleaners had the highest (0.27 mGy). The study underlined how crucial yearly monitoring is for determining the hazards of radiation exposure. When SMART was used to treat ultracentral lung lesions, Bryant et al. [13] found that it produced better dosimetric results than SABR. A 5.7 Gy decrease in dose to the proximal bronchial tree ($p = 0.002$) and a 7.3% increase in tumor coverage ($p = 0.002$) were seen in their analysis of 14 patients. There was no significant toxicity and 92.9% local control at the 17.2-month follow-up.

Across several clinical facilities, Hardcastle et al. [14] looked into discrepancies in cumulative dose assessment for reirradiation. Using a variety of techniques, such as rigid and deformable image registration, 24 participants evaluated head and neck (HN) and lung cases. The near-maximum cumulative doses varied significantly, ranging from 25.4 to 41.8 Gy for HN and 2.4 to 33.8 Gy for at-risk lung organs, according to the findings. But using a uniform spatial dose mapping procedure increased accuracy and consistency in reirradiation dose estimation. Radiation damage accumulation in Fe-9Cr under pulsed irradiation settings pertinent to inertial fusion energy (IFE) reactors was examined by He et al. [15].

They compared pulsed and continuous irradiation scenarios and examined the growth of defect clusters at various temperatures and pulse frequencies using stochastic cluster dynamics (SCD) simulations. In contrast to constant irradiation, the study discovered that pulsed irradiation typically restricts the formation of helium-vacancy clusters. Clusters of self-interstitial atoms continue to form, but under pulsed conditions, their concentrations are still much lower. Damage estimates were in good agreement with experimental data when Kim et al. [16] examined radiation damage and helium accumulation in Al-B_4C neutron absorbers. They discovered helium-induced porosification, which most likely promoted corrosion.

In order to improve safety assessments in nuclear facilities, Guo et al. [17] developed a real-time method for estimating human exposure to radiation using a dynamic 3D radiation field. They created a comprehensive simulation by integrating radiation, neutron radiation, and radioactive aerosol concentration fields, and they also introduced an optimized data loading method to increase the speed and efficiency of real-time exposure estimation. A molecular dynamics framework was created by Abolfath et al. [18] to study the interactions of nano-bubbles created by ionizing radiation at extremely high dose rates. Their research simulated thermal spikes (TS), which cause sudden thermodynamic changes in liquid water after high-energy particle passage. They examined shock wave production, bubble stability, and nanobubble mergers using reactive force field (ReaxFF) simulations, offering insights into the consequences of ultra-high dose rate radiation that may be pertinent to FLASH treatment.
A critical assessment of modeling frameworks for radiation-induced lymphopenia (RIL), a frequent side effect of radiation therapy, was carried out by Cella et al. [19]. Their research emphasizes the negative effects of RIL on treatment results and the necessity of standardized modeling techniques to enhance forecasting and create radiation therapy plans that spare immunity. In the ProtherWal proton therapy center, Ramoisiaux et al. [20] carried out a simulation research on ambient dose levels with an emphasis on radioactive shielding decay. They demonstrated the efficiency of Low Activation Concrete (LAC) in lowering radiation exposure by modeling the activation and decay radiation of concrete shielding using BDSIM and FISPACT-II. Using the γ-H2AX biomarker, Młynarczyk et al. [21] created Bayesian techniques for radiation dose calculation that take uncertainty in the period since exposure into consideration. Compared to conventional techniques that depend on preset post-irradiation times, their method enhances accuracy. Additionally, they improved computing performance by using the Laplace approximation, proving the model's applicability with actual data.

Using the CARI-6M model, Okedeyi et al. [22] evaluated the yearly cosmic radiation exposure of flight crews in local Nigerian carriers. According to their research, annual effective doses (AED) were far lower than the suggested limit of 20 μSv y^{-1}, ranging from 0.230 to 1.90 μSv y^{-1}. On the Lagos-Kano route, however, the annual gonadal dose equivalent (AGDE) in 2017 was higher than the allowable limit of 300 μSv y^{-1}. The results show a modest AED but point to a possible cumulative exposure risk for long-term cancer. The study suggests training initiatives and legislative actions to reduce flight crews' exposure to radiation. Finally Laurier et al. [23] examined the scientific basis for the use of the linear no-threshold (LNT) model in radiological protection. Their research found that while some biological mechanisms may not follow strict linearity, early-stage carcinogenesis exhibits a linear response to doses as low as 10 mGy.

III. METHODOLOGY

This study employs an analytical mathematical modeling approach to describe the accumulation of radiation dose over time for a worker exposed to a radioactive source with decaying activity. The methodology follows these key steps:

A. Governing Equations

We model the radiation dose accumulated by a worker exposed to a radioactive source with decaying activity. The dose rate $v(t)$ is proportional to the source's activity, which follows exponential decay. The total accumulated dose $D\ (t)$ is governed by the differential equation:

$$\frac{dD}{dt} = v(t) = v_0 e^{-\mu t},$$

Where:
v_0: Initial dose rate (mSv/hr),

μ: Decay constant (hr^{-1})

Separate the differential equation to isolate *dD* and *dt*:

$$dD = v_0 e^{-\mu t} dt.$$

Integrate from the initial condition $t = 0$, $D = D_0$ to a general time *t*:

$$\int_{D_0}^{D(t)} dD = \int_0^t v_0 e^{-\mu\tau} d\tau.$$

Left-Hand Side (LHS):

$$\int_{D_0}^{D(t)} dD = D(t) - D_0$$

Right-Hand Side (RHS): Factor out v_0 :

$$v_0 \int_0^t e^{-\mu\tau} d\tau.$$

The integral $\int e^{-\mu\tau} d\tau$ is solved as:

$$\int e^{-\mu\tau} d\tau = -\frac{1}{\mu} e^{-\mu\tau} + C.$$

Apply limits 0 to t:

$$v_0 \left[-\frac{1}{\mu} e^{-\mu\tau}\right]_0^t = v_0 \left(-\frac{1}{\mu} e^{-\mu t} + \frac{1}{\mu}\right)$$

Simplify:

$$\frac{v_0}{\mu}(1 - e^{-\mu t})$$

Equate LHS and RHS:

$$D(t) - D_0 = \frac{v_0}{\mu}(1 - e^{-\mu t})$$

Solve for $D(t)$:

$$D(t) - D_0 = \frac{v_0}{\mu}(1 - e^{-\mu t}).$$

B. For short term exposure: $t \ll 1/\mu$

Expand $(e^{-\mu t})$ using Taylor series we obtained:

$$e^{-\mu t} \approx 1 - \mu t + \frac{(\mu t)^2}{2} - \cdots$$

Substitute into $D(t)$

$$D(t) \approx D_0 + \frac{v_0}{\mu}(1 - (1 - \mu t)) = D_0 + v_0 t.$$

For small t dose accumulation is approximately linear

C. for long term exposure

$t \gg 1/\mu$ As $t \to \infty$, $e^{-\mu t} \to 0$:

$$D_{\text{max}} = D_0 + \frac{v_0}{\mu}$$

The dose asymptotically approaches a maximum value

The Sensitivity to Initial Dose Rate v_0 can be expressed as:

$$\frac{\partial D}{\partial v_0} = \frac{1}{\mu}(1 - e^{-\mu t}).$$

The Sensitivity to Decay Constant can be expressed as:

$$\frac{\partial D}{\partial \mu} = -\frac{v_0}{\mu^2}(1 - e^{-\mu t}) + \frac{v_0 t}{\mu} e^{-\mu t}.$$

Assume uncertainties δv_0 and $\delta\mu$. The total uncertainty in $D(t)$

$$\delta D = \sqrt{(\frac{\partial D}{\partial v_0}\delta v_0)^2 + (\frac{\partial D}{\partial \mu}\delta\mu)^2}.$$

The decay constant μ is related to the half-life $t_{1/2}$ by

$$\mu = \frac{\ln 2}{t_{1/2}}$$

Substitute into $D(t)$

$$D(t) = D_0 + \frac{v_0 t_{1/2}}{\ln 2}\left(1 - e^{-\frac{\ln 2}{t_{1/2}}t}\right)$$

IV. EXPERIMENTAL RESULT

Figure 1.0 illustrates that sources with shorter half-lives (4 hours) accumulate radiation quickly at first but plateau earlier due to the rapid decay of the radiation source. On the other hand, sources with longer half-lives (16 hours) continue to accumulate radiation at a higher rate over time, resulting in significantly higher long-term exposure. These results suggest that while shorter half-life sources pose an immediate radiation risk, longer half-life sources present a more prolonged and cumulative radiation risk.

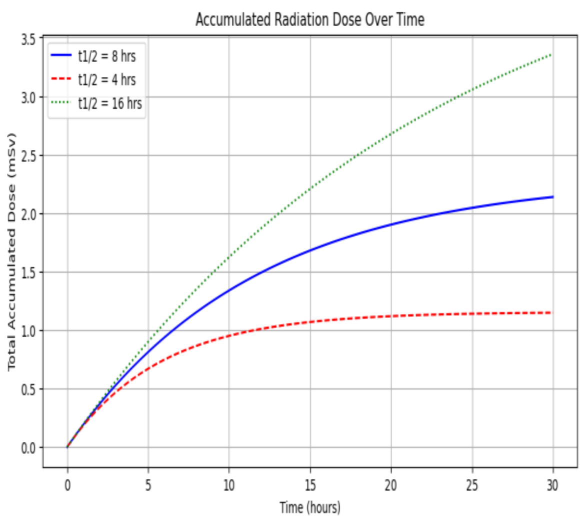

Figure 1.0 Accumulated Radiation dose over Time

Figure 2.0 shows how uncertainties in the initial dose rate (v_0) and decay constant (μ) affect the accumulation of radiation dose over time. The black line represents the expected dose accumulation under normal conditions. The blue shaded region highlights the uncertainty in the initial dose rate, with a larger spread at longer times, indicating that changes in the initial dose rate lead to a more significant variation in long-term radiation exposure. The pink shaded region, representing the uncertainty in the decay constant, shows a smaller but still notable effect on the dose accumulation. Overall, the results suggest that while both the initial dose rate and decay constant contribute to uncertainty in dose predictions, variations in the initial dose rate (v_0) have a greater impact on the total accumulated dose over extended periods.

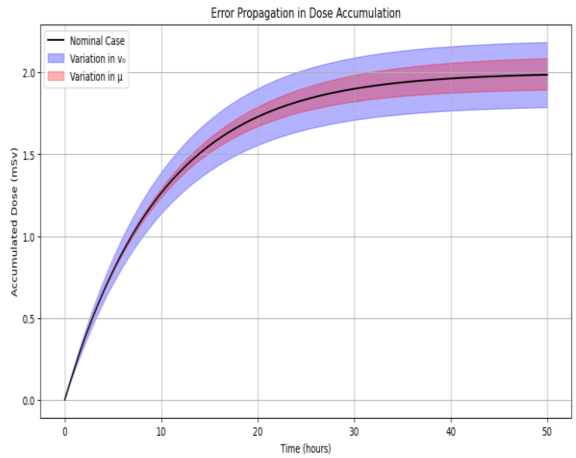

Figure 2: Error Propagation in Dose Accumulation

Figure 3 illustrates how dose accumulation is sensitive to different initial dose rates over time, with scenarios of 0.1, 0.2, and 0.3 mSv/hr leading to corresponding increases in accumulated dose. The results show that higher initial dose rates lead to significantly greater radiation exposure, although the dose increase slows and approaches a saturation point as time progresses, due to the decay factor. This implies that while higher initial dose rates cause faster radiation accumulation, the exposure eventually stabilizes over time. The key implication of these findings is that controlling the initial dose rate is crucial for managing long-term radiation risk, as higher starting doses lead to a more significant cumulative effect despite eventual stabilization.

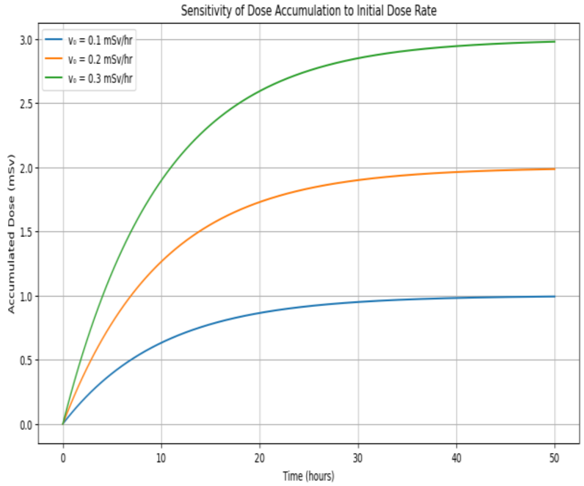

Figure 3: Sensitivity of Dose Accumulation to initial Dose Rate

Figure 4 illustrates the impact of different decay rates on dose accumulation over time. The results show that when the decay rate is low (0.05 per hour), the accumulated dose increases significantly over time. As the decay rate increases (0.1 and 0.2 per hour), the rate of dose accumulation slows down, and the dose reaches a stable point earlier. This suggests that higher decay rates lead to lower long-term radiation exposure. The implication of these results is that controlling or increasing the decay rate can be an effective strategy for reducing prolonged radiation risks, as it limits the total accumulated dose over time.

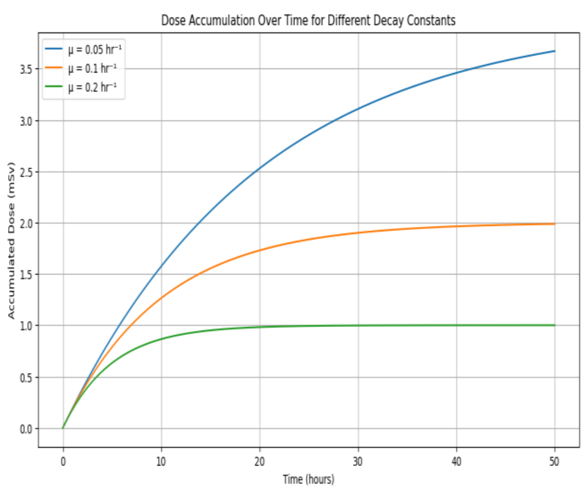

Figure 4: Dose Accumulation Overtime for Different Decay Constant

Figure 5: illustrates the radiation dose rate decay over time for three different half-lives (4, 8, and 16 hours). The results show that the dose rate decreases exponentially, with shorter half-lives (4 hours, shown by the red dashed line) experiencing a rapid decline, while longer half-lives (16 hours, shown by the green dotted line) result in a slower decay, maintaining higher radiation levels over a longer period. This demonstrates that sources with shorter half-lives present a quick but temporary radiation risk, whereas those with longer half-lives pose a prolonged risk. The implication is that longer half-lives require extended protective measures to mitigate sustained exposure.

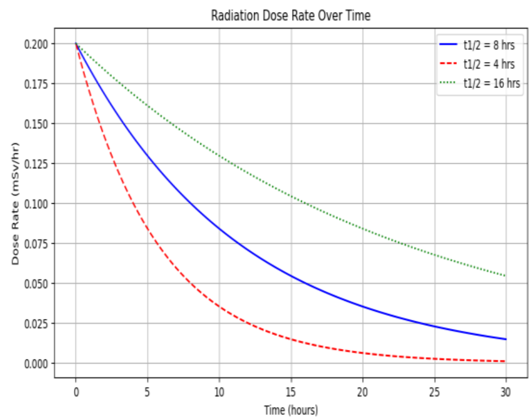

Figure 5: Radiation Dose Rate Over Time

Figure 6: illustrates the difference between short-term and long-term dose accumulation over time. The short-term approximation (blue dashed line) follows a linear trend, suggesting continuous and unlimited accumulation. However, the actual long-term dose accumulation (red solid line) rises initially but eventually levels off near a maximum dose limit (D_{max}, black dotted line). This indicates that in real-world scenarios, factors such as biological adaptation, elimination processes, or system saturation prevent indefinite accumulation. The key takeaway is that short-term exposure models can overestimate risks if long-term saturation effects are not considered.

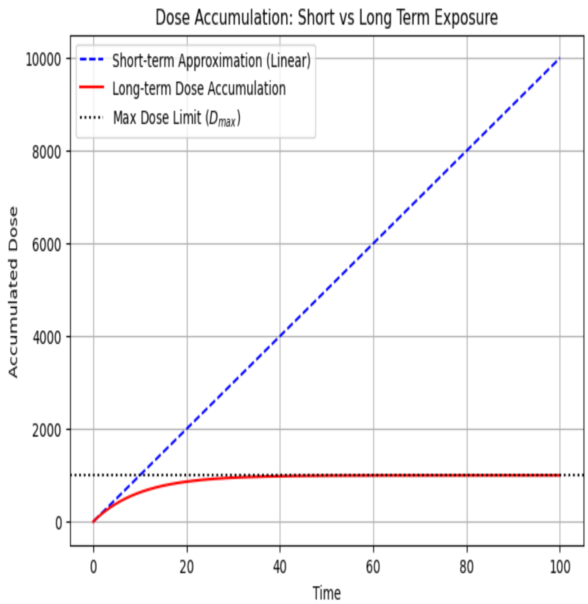

Figure 6: Dose Accumulation: Short vs Long Term Exposure

CONCLUSION

This study highlights the critical influence of decay constants, half-lives, and initial dose rates on radiation dose accumulation, providing valuable insights for radiation protection and health physics. The results demonstrate that sources with shorter half-lives and lower decay constants cause rapid initial dose accumulation, but this rate decreases and stabilizes over time. In contrast, sources with longer half-lives and higher decay constants lead to a slower decay and prolonged exposure. These findings emphasize the need for careful management of decay rates and exposure durations, especially in environments with radioactive materials. The ability to control these factors is essential for minimizing long-term radiation risks and improving radiation safety protocols. This work has direct implications for radiation protection strategies, underscoring the importance of monitoring dose accumulation over extended periods to safeguard public health and reduce potential radiation-induced health effects.

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