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ENTRY SKIN DOSE REDUCTION IN AN INLINE MRI-LINAC USING AN ELECTRON CONTAMINATION DEFLECTOR COUPLED WITH A HELIUM VOLUME

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ABSTRACT

While magnetic resonance imaging (MRI) and linear accelerators (MRI-Linac) are used together for better visualizing soft-tissue prior to radiotherapy, the dosimetric issues are that secondary electron transport and entry-surface dose distribution are challenging. In MRI-Linac systems with inline beam path, dose to the skin may be overestimated due to the presence of the electron contamination in the beam. Four configurations are studied: a baseline configuration, an "electron contamination deflector (ECD)", a configuration with helium-filled volume and a combined ECD–helium. A computational radiation transport framework written in python was used to compare electron-fluence outputs, electron depth dose distributions, beam-quality parameters and dose-validation metrics. It took 200,000 primary photons in the combined configuration, and 50,000 in the baseline (ECD-only) and helium-only configurations. The numbers of surface electrons counted were: 34, 22, 16 and 27. The electron-arrival rates normalized to the number of primary photons were 6.80 $\times$ 10$^ {-4} $, 4.40 $\times$ 10$^ {-4} $, 3.20 $\times$ 10$^ {-4} $ and 1.35 $\times$ 10$^ {-4} $ electrons per primary photon. The normalized electron-arrival rate of this combined configuration was the smallest, and 80.1% descriptive reduction was obtained compared to the baseline. However, the dose-validation results of the combined configuration showed a Pearson correlation of −0.072 with the reference dose distribution and 0% gamma pass rate under the 3%/3 mm criteria. The results represent differences in the reported rates of arrival of electrons at the simulated set-ups. The results from the dose validation indicate that the dose calculated, and the reference distributions agree only to a certain degree. A comparison is made of the ECD helium configuration in the computational framework studied and their dosimetric outputs and electron-fluence and the validity of their results are interpreted.

KEY WORDS: *MRI-Linac, electron contamination, entry-surface dose, electron contamination deflector, helium volume, radiation transport, computational dosimetry, Monte Carlo simulation.*

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1. INTRODUCTION

New developments in image-guided radiation treatment (IGRT) have resulted from the combination of linacs with magnetic resonance imaging (MRI). Among the benefits is the capacity to rescue and replan patients in response to changes in both the patient and the tumor, as well as the ability to monitor the target to evaluate internal movement during treatment and better positioning verification prior to treatment. This increases the likelihood of tumor control and decreases setup mistakes (Lagendijk, et al. 2014). In addition to the target, MRI linac technology provides contrast enhancement in soft tissues and more precise tumor and organ characterizations. Dosimetry and system design are both affected by the special difficulties brought forth by the radiation beam and the high magnetic field. Clinical application of the ViewRay MRIdian with the Elekta Unity has just occurred (Raaymakers, et al 2017).

The presence of a magnetic field has been shown in several investigations over the last few decades to alter the distribution of doses. The photon beam is unchanged, but the Lorentz force changes the secondary electrons' trajectories, which affects the dosage distribution as a whole. When a transverse magnetic field is present, the dosage distribution varies dramatically on the entrance and exit surfaces and in the medium of varying densities. The source is Pojtinger et al. ("2019").

In addition, prior research has shown that many solid-state sensors and ionized chambers may alter their responses when exposed to the longitudinal field of magnets. To achieve precise dosimetry, it is necessary to use specified orientations and correction factors, as these modifications are rotational and strength of magnetic field dependent. The source is Begg et al. (2023). Additionally, it is discovered that the transverse magnetic field changes the skin dosage distribution on the entry and exit surfaces. Because of these general changes in MRI-linac beam properties, dosimetry might become more complicated. However, it has been shown that the dosage distribution and overall beam properties of megavoltage (MV) photon beam are unaffected by a longitudinal magnetic field when compared to the main beam direction. The existence of an inline magnetic field causes electrons to converge along the beam paths, according to Monte Carlo (MC) calculations, because of the Lorentz force that acts in a direction perpendicular to the main beam. Conformal the distribution of doses at depths inside a medium that is uniform is possible because the electrons are more concentrated along the beam path, which decreases lateral dispersion and reduces penumbral widths. According to Ng et al. (2023).

In the build-up area of an MV photon beam, the dosage is mostly caused by electron contamination. It depends primarily on field sizes and the surface-to-source distance (SSD), and it typically originates in the linac head, flatness filter, beam modifiers, convergence devices, and the air gap between the linac unit and the patient's surface. The inline field enhances the skin dosage because contaminated electrons are concentrated within the beam rather than scattered laterally. In 2016, Keyvanloo et al.

Surface dosage reduction due to electron pollution has been the subject of several investigations. Projector spoiler/bolus and filter techniques have been investigated in certain research; nevertheless, reintroducing electrons into the material has led to a boost in surface dosage within the phantasm in some cases. One experiment also looked at using an off-axis irradiation approach to reduce the surface dosage from electron contamination. The therapeutic efficacy of the MRIlinac is diminished due to off-axis irradiation, which decreases the available therapy field size and causes MRI pictures to exhibit increased distorted geometry and non-linearity as one move away from the MRI isocenter. An alternative method has been suggested which involves using a permanent magnet deflector to purge electron contamination from the x-ray beam,46 as well as a helium volume to reduce air-generated electron contamination. **(Hackett, et al 2018).** The scope of the present study is not as wide as the scope of a clinical validation study. The software compares the four configurations and consists of the assumptions provided on the files supplied, as well as the analysis of the output generated by a simulation package with a Python based black box.

2. METHODOLOGY

2.1. RESEARCH DESIGN AND COMPUTATIONAL FRAMEWORK

In this research, a comparative computational design is used to examine electron contamination in an inline MRI-Linac. The effect of electron contamination, helium volume and their combination of dose distribution and electron contamination are analyzed. The five stages of the research methodology are: Definition of the computational design, configuration of the design, collection of the results, comparison of the results and validation of the dose distribution.

2.2. STAGE 1: DEFINITION OF THE COMPUTATIONAL MODEL

The first stage represents the computational framework which is used to compute the MRI-Linac delivery geometry. The calculation model contains the following variables: magnetic field, properties of the materials, particle transport, geometry of the phantom and the photon source.

The photons have an energy of 2 MeV, the air gap is set at 80 cm, the surface to phantom distance is 100 cm and the thickness of the phantom is 30 cm for a 6 MV photon beam. It is composed of the air accumulation phantom, superficial phantom and deep soft tissue phantom. Material properties and the size of the geometry are the major features of the environment for the analysis of electron transport and energy deposition.

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The model of photon interaction and secondary electron transport is carried out by using the same transport that is implemented in the computational framework. Also, the magnetic field is assumed during the modeling process since the magnetic field can affect particle transport. How the magnetic field is assumed depends on the implemented model.

2.3 STAGE 2: SIMULATION OF THE FOUR CONFIGURATIONS

Four different arrangements are tested based on the aforementioned computational conditions in order to assess the impact of individual mitigation mechanisms and their combination.

1. Control configuration: Control configuration without a helium volume or electron contamination deflector. This is a condition used as a standard for comparison with other conditions.
2. Electron contamination deflector configuration: The electron contamination deflector is composed of an aluminum foil with nominal thickness of 0.1 cm with designed electron stopping efficiency of 0.92. It has been studied how it affects the electron contamination recorded.
3. Helium only configuration: This arrangement has a 20 cm helium filled volume with a density of 0.0001663 g/cm³ added to investigate the impact related to the replacement of air volume by the helium one.
4. Arrangement featuring both electron contamination deflector and helium volume: This arrangement includes both electron contamination deflector and helium volume in order to compare this particular arrangement against baseline and individual mitigation arrangements.

All saved arrangements have 50,000 primary photons for control, electron contamination deflector only and helium only configurations and 200,000 primary photons for the last configuration.

2.4 STAGE 3: EXTRACTION OF COMPARATIVE OUTCOMES

Following the simulations, the results concerning electron-fluence, depth-dose, beam-quality, and validation are analyzed. There are three major types of outcomes which are evaluated: normalized electron yield, electron-fluence, and absorbed skin dose.

Normalized electron yield is defined as the ratio of the number of electrons measured at the skin surface of the phantom to the number of simulated photons. The equation is given below:

$$R_e = \frac{N_{e,\,\text{skin}}}{N_{\text{primary}}}$$

where R_e is the normalized electron yield, $N_{e,\,\text{skin}}$ is the observed number of electrons penetrating the skin, and N_{primary} is the number of primary photons for this particular setting.

The electron fluence is analyzed in order to describe the electron distribution observed. The skin dose is analyzed based on the obtained results for the skin dose, where available, in order to analyze energy deposition within the surface phantom region. These three measures are considered separately since they correspond to different physical quantities.

2.5 STAGE 4: QUANTITATIVE COMPARISON AND UNCERTAINTY ANALYSIS

Comparison between the results is done in the fourth step. This is done by comparing the normalized electron yield of each mitigation strategy to the baseline using the percent change equation:

$$\Delta R_e(\%) = \frac{R_{e,\,\text{baseline}} - R_{e,\,\text{case}}}{R_{e,\,\text{baseline}}} \times 100$$

where $R_{e,\,\text{baseline}}$ is the normalized electron yield for the baseline configuration and $R_{e,\,\text{case}}$ is that for the ECD-only, helium-only, or combination configuration. If the number is positive, it signifies a lower normalized electron yield than the baseline.

This same idea is used for comparing absorbed skin dose where reliable dose measurements exist. Percentage differences in electron yields do not represent percentage differences in absorbed doses.

When comparing different configurations, the results of the simulated histories are considered. By performing multiple runs with different random numbers, the uncertainties in the results can be evaluated. This is different from the descriptive normalization of the existing particle counts since the uncertainties in multiple runs are not inferred solely from the particle counts.

2.6 STAGE 5: VALIDATION OF THE DISTRIBUTION

The last step is to check the consistency of the dose distribution and compare it to a measuring reference, if available. A percentage depth-dose (PDD) curve is employed to find out the depth of maximum dose, fall in dose thereafter and also irregularities in the calculated dose distribution.

The quantitative validation is comprised of Pearson correlation and gamma analysis; root means square error (RMSE) and means absolute error (MAE) with 3%/3 mm criteria. These measures indicate the size of dose differences; how the dose differences relate to both the calculated and reference doses and how well they match the specified gamma criterion.

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The validation metrics are discussed along with the PDD curves and other output provided of the dose. Their interpretation is dependent on the appropriateness of the reference distribution, uniformity of dose normalization, and spatial registration. Thus, this stage does not give the low number of electrons as an indication of the correctness of the dose-model, rather, an independent assessment on the agreement between dose distribution.

3. RESULTS AND DISCUSSION

3.1. RECORDED SURFACE-ELECTRON COUNTS

The number of electrons detected on the surface was not the same in all four simulation settings. In the case of the base setting, 34 electrons were detected, whereas in the case of ECD only 22 electrons were detected, in the case of helium only 16 electrons were detected and in the case of ECD with helium 27 electrons were detected. The primary photons history in the case of base, ECD only and helium only settings were 50,000, while in the case of combined setting it was 200,000.

Table 1: Comparison of recorded surface-electron counts across the four configurations.

Configuration	Primary photons	Electrons at skin	Electrons per primary photon
Baseline	50,000	34	6.80×10^{-4}
ECD only	50,000	22	4.40×10^{-4}
Helium only	50,000	16	3.20×10^{-4}
ECD + helium	200,000	27	1.35×10^{-4}

The normalized electron-arrival rate was found by taking the number of electrons detected by the skin and dividing by the number of primary photons in the simulation. According to these findings, the minimum electron-arrival rate is seen as the combination of ECD and helium followed by helium alone, ECD alone, and baseline configuration.

Compared to the baseline normalized rate, there was 35.3% reduction for ECD-only configuration, 52.9% for helium-only, and 80.1% for the combination. It must be noted that these percentages describe a difference in the number of electrons normalized but not the reduction of absorbed skin dose. Therefore, from these findings it is clear that the minimum electron-arrival rate was achieved in the combination of ECD and helium configuration.

3.2. DOSE AND BEAM-QUALITY OUTPUTS.

Beam-quality depth-dose at d_{max} of approximately 4.9 cm and d50 of approximately 24.9 cm is shown for the combination. Values of d_{max} and d50 for individual configurations are provided as well, close to these depths. Such values must be treated with caution: the depth-dose files exhibit significant non-monotonic behavior at depth, with both peaks and zero-valued bins present. It is explicitly stated in the validation report that the behavior of the PDD is non-monotonic at depths greater than d_{max} in 19 out of 121 voxels. This behavior is insufficient to produce a reliable depth-dose curve.

The combined validation shows photon survival of 0.0 and failed self-consistency check. Comparison with the measurement reference results in the following: mean absolute difference 53.72 percentage points, root-mean-square difference 59.15 percentage points, Pearson correlation -0.0718, and gamma pass rate 0.0% at 3%/3 mm. This set of indicators suggests that the computation currently is not a valid representation of the reference distribution. Reported relative errors are very high, which is probably due to division by very low or zero reference values.

3.3. FOUR-CASE COMPARISON ANALYSIS

The four cases represent a comparison of the number of electrons collected from the baseline, ECD only, He only and ECD + He configurations. Lower number of recorded skin electrons was found for each single mitigation method compared to baseline. The ECD+ is normalized to the number of input photons (primary photons). Helium and Helium arrival rates were lowest and Blended He/Helium was better than ECD alone. These results are in line with the complementary behavior between ECD and helium volume, and differences in electron transport for the different configurations.

However, absorbed dose in the skin and the rate of arrival of the electrons are two different types of doses. There are other factors that are important in determining the absorbed dose of radiation, such as the amount of incident electrons on the phantom skin, the energy distribution of the electron, and the mass of the scoring volume. With respect to ECD+ we observed a quantitative reduction in the electron yield of 80.1%. The set-up is not suitable for estimating the dose reduction.

The results of the dose-validation study can be seen as another point of view on the comparison of the four cases under investigation. The difference between the number of electrons is not enough to show any change in the dose to the skin since the agreement between the simulated and reference dose distributions is poor. Based on this, the study results show differences between the four cases studied in the normalized arrival rate of electrons while the dose outputs are not consistently enough with reference distribution.

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4. DISCUSSION

In this comparison, the outputs of four MRI-Linac simulator setups are compared with each other. The relative rank as determined by raw data is modified by normalizing the electron counts from skin to total number of primary photons. For the baseline setup there were 34 skin electrons and for the combined setup, 27 skin electrons. At the same time, the combined setup required 200,000 primary photons, whereas the other setups only required 50,000 primary photons. After combining setups, they were able to generate the lowest number of skin electrons per primary photon. This comparison gives an insight into the saved result of the simulation and the variation of skin electrons of the different setups.

5. LIMITATIONS

There is no separate radiation transport experiment performed for this project that is used in the analysis: the stored outputs and configurations of the simulation are used. The outputs are not provided with an uncertainty range for the observed electron counts and the difference between the four configurations is due to the history of the photons. The intent of the validation report is to create criteria of comparison to be used in this analysis, but it does not report actual data obtained nor the uncertainty of the detector, so it is not located in the project archive. This analysis therefore assumes that the reduction in skin dose is as reported in the output as an independent experimental assessment of the reduction in skin dose is not performed.

6. CONCLUSION

The comparison of baseline, ECD alone, helium alone, and combined ECD-helium configurations concerning electron contamination in an inline MRI-Linac scenario was done using the Python-based framework. The number of electrons counted on the skin in each case was 34, 22, 16, and 27, respectively. Based on the number of primary photons, the lowest electron arrival rate was observed in the combined configuration followed by helium alone, ECD alone, and baseline. This order reflects a description of the comparison of the recorded counts and cannot be used interchangeably with the percent reduction in the skin absorbed dose. In regard to the dose-related output, there is poor concordance with the reference dose, including 0% gamma pass rate and Pearson correlation of -0.0718 for the combined configuration. Therefore, in summary, the output results describe the differences between the four simulated configurations while reflecting that the electron counts recorded and dose validation metrics constitute different types of evidence.

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