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Development of a Simplified Intravascular Brachytherapy Treatment Planning System Using Monte-Carlo Derived Dose Data

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Purpose: The goal of this study is to develop a simple treatment planning system (TPS) to assess the dosimetry of a Y-90 source train-based treatment for intravascular brachytherapy (IVBT) using data from Monte-Carlo simulations.

Method and Materials: Using a Monte-Carlo simulation that was already built in Geant4, an accurate dose distribution was obtained of an IVBT treatment using a source train of Y-90. A simple TPS was designed using Python to overlay the dose distribution onto the great vessel of an anonymized cardiac CT scan. Dose normalization and remapping were accomplished by utilizing the pydicom, SimpleITK, and numpy Python libraries. Dose Volume Histograms (DVHs) were created to assess the dose to the heart, vessel walls, and lungs. Moreover, to simulate the positional uncertainty of the catheter, dose distributions were calculated in Monte-Carlo after shifting the catheter by a specified amount laterally in the blood vessel. This was then used to calculate DVH's for the great vessels and then graphed onto the same plot for dosimetric analysis.

Results: Other than the blood vessel wall around the catheter, the dose to the heart and lungs is orders of magnitude lower than the prescription dose. This is expected as the dose from beta sources falls quickly with distance. The dose to the vessel wall, however, fluctuates significantly (>9 %) from the prescription dose, depending on the shift of the catheter.

Conclusion: We have developed a simple TPS using data from Monte-Carlo simulations to assess the dosimetry of a Y-90 source train-based IVBT. The results reaffirm IVBT is a highly localized treatment with negligible radiation doses to heart and lungs. The positional uncertainty, however, introduces fluctuations to the dose distribution to the vessel wall.

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INTRODUCTION

Intravascular brachytherapy (IVBT) is a specialized form of radiation therapy used to treat conditions such as restenosis by delivering radiation directly within blood vessels. Among the available radionuclides, yttrium-90 (Y-90) is commonly employed due to its high-energy beta emission and rapid dose falloff, which enable highly localized treatment while sparing surrounding healthy tissue. In this study, we develop a simplified treatment planning system based on Monte Carlo–generated dose distributions to evaluate the dosimetry of a Y-90 source train–based IVBT procedure. By integrating simulation data with patient imaging and assessing dose variations resulting from catheter displacement, this work aims to provide insights into dose delivery accuracy and the sensitivity of vessel wall dosing to positional uncertainties.

METHODS AND MATERIALS

An accurate dose distribution for an IVBT treatment using a Y-90 source train was obtained through a Monte Carlo simulation implemented in Geant4 [1]. The package was installed on an independent workstation with an Ubuntu 22.04.5 operating system. The physics processes simulated included Compton, photoelectric, and pair production for photons; electron ionization, continuous slowing down approximation (CSDA) model, and bremsstrahlung for electrons and positrons. The PENELOPE (Penetration and Energy Loss of Positrons and Electrons) models of GEANT4 were chosen for the electromagnetic processes. This particular installation of GATE including all physics processes modeled has been validated for accuracy in a previous study by Chang et al. [2].

A simplified treatment planning system (TPS) was developed in Python to overlay the simulated dose distribution onto the great vessel of an anonymized cardiac CT dataset (Figure 1). Dose normalization and spatial remapping were performed using the pydicom, SimpleITK, and NumPy libraries. Dose–volume histograms (DVHs) were generated to evaluate dose distributions to organs at risk, including the heart, vessel walls, and lungs.

The Beta-Cath delivery system lacks a mechanism to center the source within the guide catheter or to center the guide catheter within the vessel. As a result, positional variations may occur, causing the source to move closer to or farther from the vessel wall within the geometric constraints of the catheter and vessel diameter.

To account for this positional uncertainty, additional Monte Carlo simulations were conducted with specified lateral displacements of the catheter within the vessel. The resulting dose distributions were used to generate DVHs for the great vessels, which were plotted together to enable comparative dosimetric analysis.

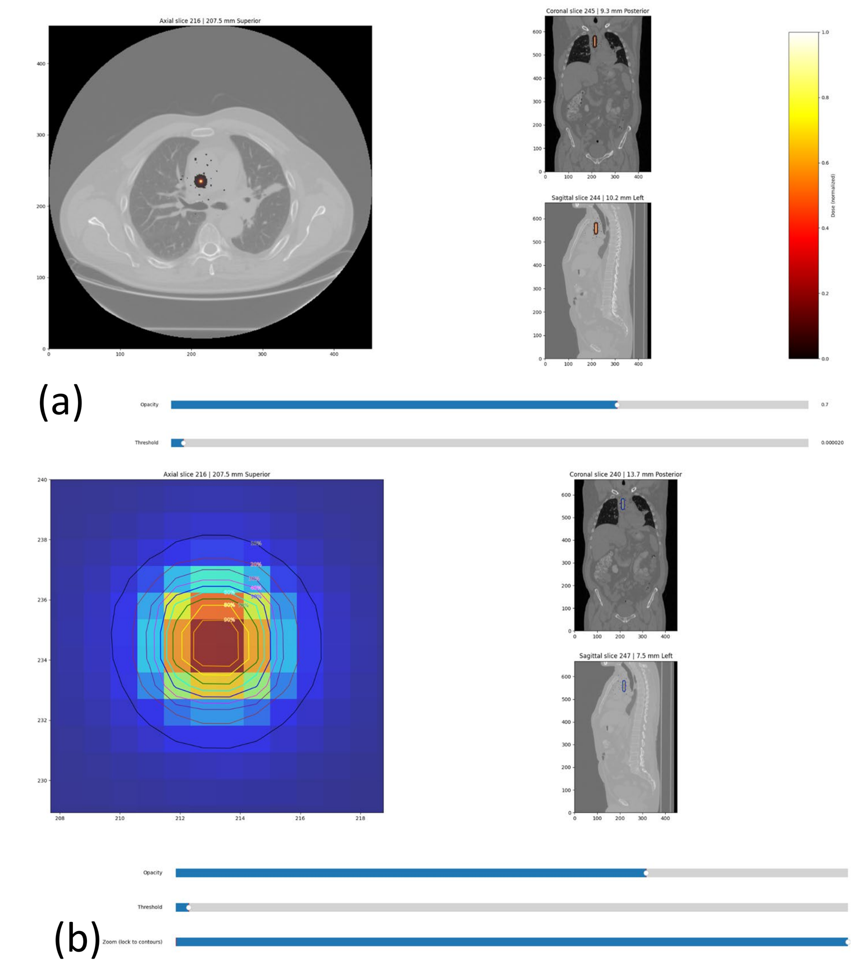

Figure 1: (a) Dose overlay with anonymized CT sca shown in 3 planes. (b) Isodose contou overlaid on an anonymized CT sca shown in 3 planes.

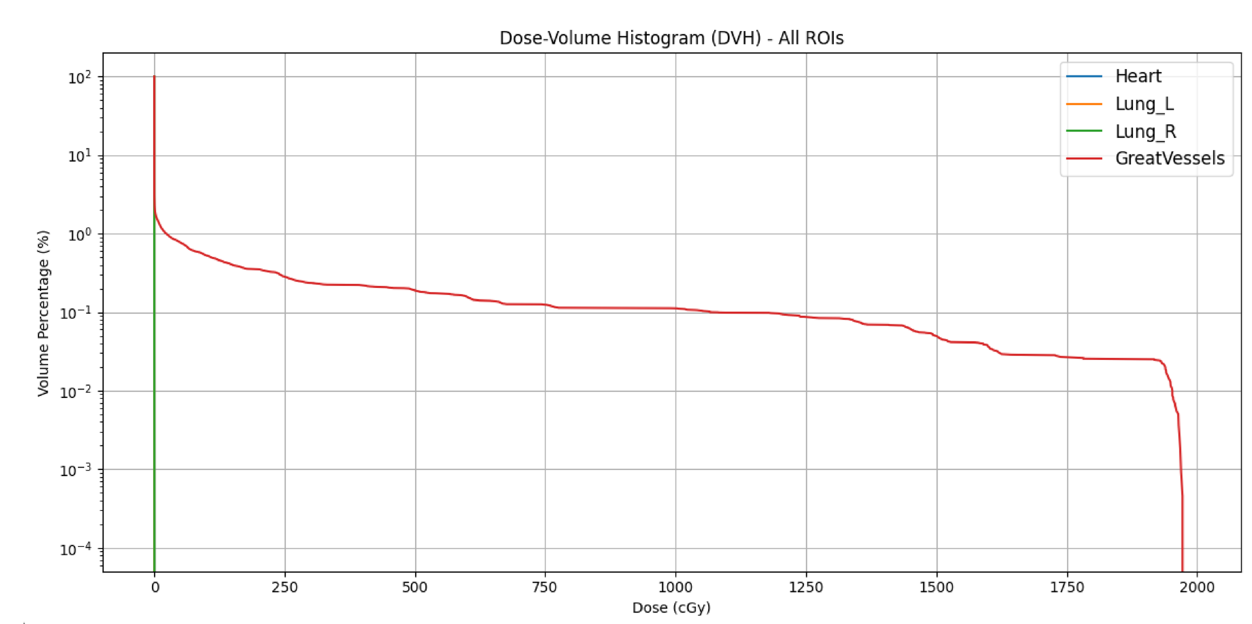

Figure 2: Dose-volume histograms comparing dose distributions across multiple anatomical structures for a Y-90 source train IVBT treatment, displayed with a logarithmic volume scale.

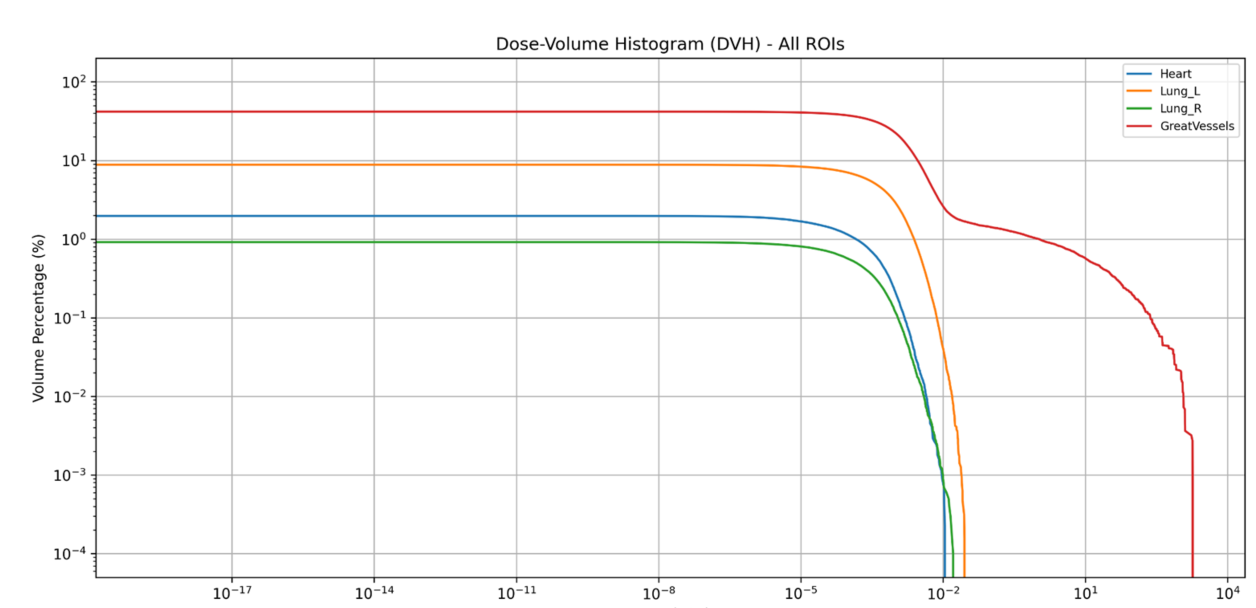

Figure 3: Dose-volume histograms for the same set of structures as in Figure 2, shown using logarithmic scaling on both the dose and volume axes to expand the dynamic range of the distribution.

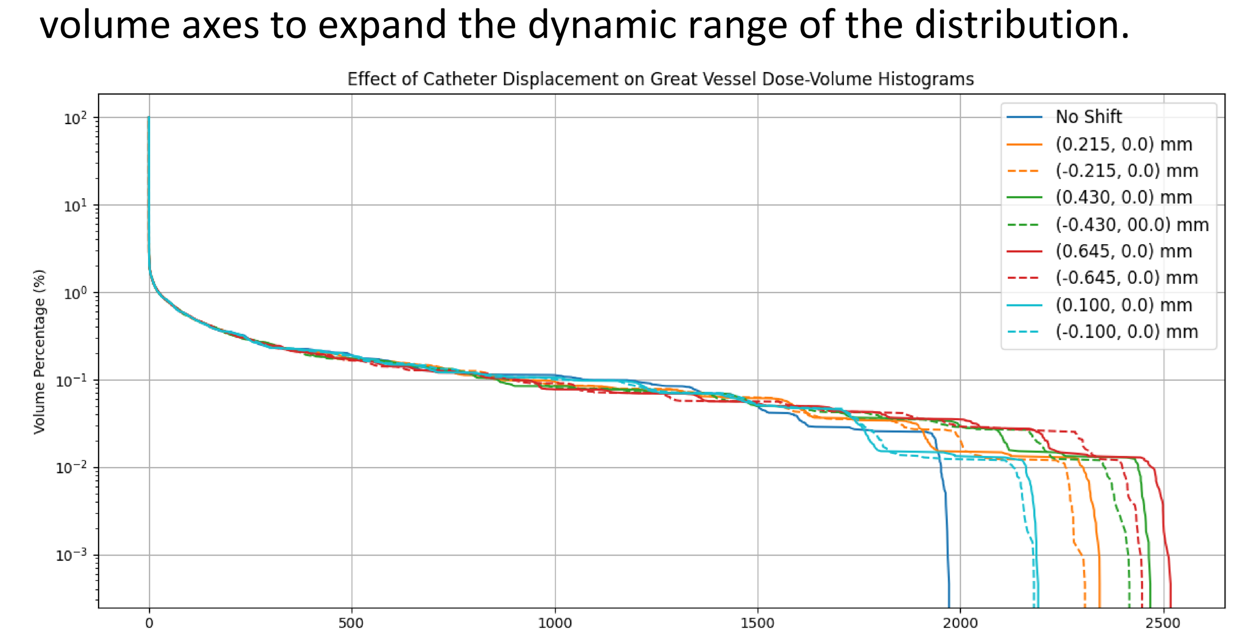

Figure 4: Dose-volume histograms of the great vessel under a series of applied lateral catheter displacements, illustrating the set of positional configurations evaluated.

RESULTS

As shown in Figures 2 and 3, the dose delivered to the heart and lungs is several orders of magnitude lower than the prescription dose, except in the immediate vicinity of the vessel wall surrounding the catheter. This behavior is expected, as beta radiation exhibits a rapid dose falloff with increasing distance from the source. In contrast, the dose to the vessel wall shows significant variation (greater than 9% relative to the prescription dose), depending on catheter displacement, as illustrated in Figure 4.

DISCUSSION

This study demonstrates that a simplified TPS can effectively characterize the dosimetry of Y-90 source train–based IVBT. The resulting DVHs confirm the inherently localized nature of beta radiation, with rapid dose falloff leading to minimal exposure to surrounding organs.

A key finding is the sensitivity of vessel wall dose to catheter displacement: increasing lateral displacement within the vessel results in higher dose to the vessel wall. Notably, the dose distribution is asymmetric, as equal positive and negative displacements do not yield equivalent vessel wall doses, with the deviation increasing at larger shifts. This unexpected result warrants further investigation in future studies.

Several limitations should also be considered, including the simplified representation of catheter and vessel geometry, the assumption of homogeneous tissue composition, the absence of organ motion, and the lack of patient-specific modeling.

CONCLUSIONS

We developed a simplified TPS based on Monte Carlo simulation data to assess the dosimetry of a Y-90 source train–based IVBT procedure. The results reaffirm that IVBT is a highly localized treatment, delivering negligible radiation doses to the heart and lungs. However, positional uncertainty introduces notable variations in the dose distribution to the vessel wall.

REFERENCES

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