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STUDY AND EVALUATION OF DOSE CALCULATION ALGORITHM IN HETEROGENEOUS ENVIRONMENTS FOR PHOTON RADIOTHERAPY USING TRUEBEAM STX LINAC

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INTRODUCTION

Today, new generations of radiotherapy linear accelerators are often equipped with many new features and can perform many modern techniques such as intensity-modulated radiotherapy and radiosurgery. However, the requirement for accuracy in calculating patient dose distribution is also stricter. International recommendations for overall dose error require less than 5%, and recent recommendations are 3% to 3.5%.

The overall error is contributed by many components in a radiotherapy procedure. According to statistics, errors related to radiotherapy planning range from 2% or more. Each radiotherapy planning software integrates several different dose calculation algorithms; each algorithm uses different physical theories and calibration methods to calculate the dose, especially in heterogeneous density environments like the human body, calculating the exact required dose is more challenging due to disturbances in the distribution of radiation fields and charges in areas adjacent to the environments.

Many domestic and foreign studies have partly shown the significance and need to learn about effectiveness and effects of radiotherapy dose calculation algorithms on patients. However, domestically and internationally, no comprehensive studies have evaluated the accuracy of dose calculation algorithms in heterogeneous density environments using simulation tools (Monte Carlo) and experimental measurements using an ionization chamber, especially research with all clinical application beams of the TrueBeam STx linac. The TrueBeam STx with Eclipse treatment planning system is the most modern generation of radiotherapy linac that is increasingly popular in Vietnam. The linac can emit flattened-filtered (FF) and flattened-filtered free (FFF) photon beams with

many outstanding advantages, combined with new generation algorithms (AAA, XXB) applied in dose calculation for many techniques, the most advanced radiotherapy available today.

For the above reasons, the study and specific evaluation of several algorithms applied in clinical radiotherapy and simultaneous verification by experimental measurements on phantom and Monte Carlo simulation were divived for this study.

* The thesis is carried out with two goals:

1. Evaluate the suitability of Monte Carlo PRIMO and GATE simulation results for the photon beam physical characteristics used in the TrueBeam STx linac clinical radiotherapy.

2. Research and evaluate the dose distribution calculation accuracy of the AAA and AXB algorithms for photon beams in heterogeneous environments like the human body.

* Main research contents:

1. Simulate and study the physical characteristics of the photon beam of the TrueBeam STx linac using Monte Carlo tools (GATE, PRIMO) and measure experimentally with an ionization chamber.

2. Research and evaluate algorithms (AAA, AXB) based on calculations on TPS, simulating, and experimentally measuring the percentage depth dose using a multi-layer phantom of heterogeneous density.

3. Research and evaluate algorithms (AAA, AXB) based on calculations, Monte Carlo simulation, and experimental dose distribution measurement using a chest phantom (E2E SBRT) equivalent to the human body.

4. Research and evaluate algorithms (AAA, AXB) based on Monte Carlo calculations and simulations of some actual radiotherapy plans.

CHAPTER 1. OVERVIEW

1.1. Overview of radiotherapy

Radiation therapy is the process of using high-energy ionizing radiation to kill cancer cells. The standard linac radiotherapy procedure includes CT simulation, treatment planning, quality assurance plan measurement to confirm the plan, irradiation on linac, and patient following. Successful radiotherapy requires precision in planning, including precision in dose calculation algorithms.

Accelerators are indispensable equipment in external radiotherapy. The linac structure includes three main systems: electron generation, acceleration and transport, and beam shaping. General operating principle: electrons are generated from the electron gun, sprayed into the accelerator tube, and the accelerated electron beam hits the target to create bremsstrahlung radiation or is used directly for treatment.

The physical principle of dose calculation is based on the interaction of radiation (photons, charged particles) with matter, and the total dose absorbed by the environmental matter includes the dose contribution of primary and secondary radiations.

1.2. Some physical characteristics of radiotherapy photon beams

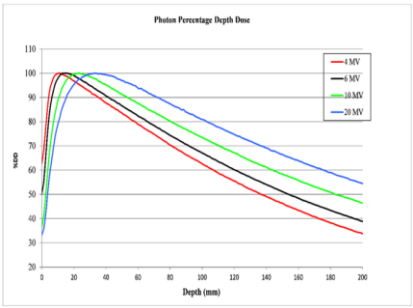


Figure 1.4. Percent depth dose distribution according to FF photons

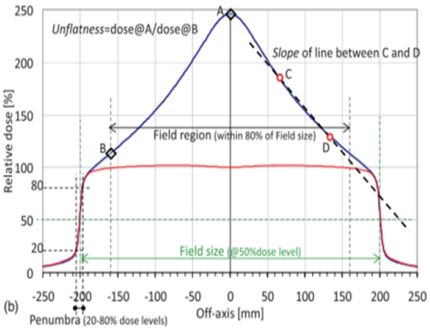


Figure 1.5. Profile of the FFF and FF photon beams

- Percentage depth dose (PDD) is the ratio of the absorbed dose at any depth on the beam's central axis compared to the dose at reference depth (usually the maximum dose-D_{max}). From PDD, determine dose D_{max}, maximum dose depth (z_{max}), beam quality coefficient k_Q ($TPR_{20/10}$), and surface dose D_s.

- A profile represents the relative dose in the off-axis distance at a certain depth. Profile allows for the determination of the dose field size of the beam, flatness, symmetry, and penumbra...

1.3. Dosimetry in radiotherapy

Dose measuring of photon beams on radiotherapy linac using ionization chambers has reliable accuracy and is the most commonly used. The dose quantity used is mainly the absorbed dose (D).

To measure the dose at a point in the environment, we must put the ionization chamber at that point; then, the ionization chamber can be considered an air cavity. The necessary condition is a charged-particle equilibrium (CPE) state in the cavity. When the volume of the gas cavity is small enough, a state of CPE is achieved when the charged particles entering and leaving that volume are equal in charge and energy. This is the basis of the Bragg-Gray and Spencer-Attix gas cavity theory, which establishes a relationship between dose in the gas cavity (Dair) and dose in the medium (Dmed). The difference is that in the Spencer-Attix theory, the dose contribution of delta electrons is taken into account.

** Calibration of ionization chamber in measuring and calibrating of radiation therapy absorbed dose:*

Absolute dose measurement using an ionization chamber is based on documents such as IAEA TRS-398, TRS-483, AAPM TG-51, and DIN 6800-2. The absorbed dose in water (D_w) at the reference depth (z_{ref}) for a high-energy photon beam is given by the following formula:

$$D_w = k_Q.N_w.M \qquad (1.12)$$

k_Q: beam quality factor (energy-dependent)

N_w: normalized coefficient in water of ionization chamber

M: the electrometer reading has been corrected (electrometer, air density, ion recombination, polarization effects...)

The ionization chamber is usually calibrated with a Co-60 source, not the accelerator photon beam. However, there are differences in physical properties between the two beams, and Co-60 sources are becoming less and less common. Therefore, direct ionization chamber calibration on accelerated photon beams is essential and requires extensive research and application.

1.4. Monte Carlo simulation tool applied in radiotherapy

The Monte Carlo algorithm is considered the most accurate reference for other algorithms. Some Monte Carlo simulation tools in radiotherapy are EGS, MCNP, PENELOPE, Geant4, GATE, and PRIMO.

- GATE: built and developed on the Geant4 platform. The main interactive processes include electromagnetic, Hadronic, particle transport, decay, optical, photolepton_hadron, and parameterization. Among them, electromagnetic interactions play the most significant role. GATE is built and developed according to a layer structure, including the Geant4 core and three other layers: the core, application, and user layers. GATE uses simple commands to execute tasks as the user requests.

- PRIMO: allows linear accelerator simulation and calculation of absorbed dose distribution in water phantom and on CT images. PRIMO has pre-configured Varian and Elekta multi-accelerator models as input data needed for simulation. PRIMO adds a dose planning tool to import CT images, anatomical structures, and field settings.

1.5. Treatment Planning System and dose calculation algorithms used in radiotherapy

Treatment Planning System (TPS) is software that calculates dose distribution on patients, integrated with dose calculation algorithms. Classification of clinical radiotherapy dose calculation algorithms according to ability and dose calculation method:

- Group A algorithm: based on the vertical correction of inhomogeneity (Ray tracing or pencil beam convolution), which has low accuracy and fast calculation.

- Group B algorithm: based on vertical and horizontal correction of inhomogeneity (superposition method), on the average statistical method, and the interaction effect of a large number of particles. Convolution algorithms calculate dose with accuracy close to Monte Carlo while taking less time.

- Group C algorithm: based on Monte-Carlo algorithms or Bolztman's equations transformation (AXB) solving algorithms, allowing better correction of inhomogeneities. Monte Carlo is considered the most accurate algorithm for calculating radiotherapy dose but requires the longest calculation time.

Table 1.1. Algorithms calculate dose according to groups A, B, and C

Group A	Group B	Group C
- Pencil Peam Convolution (PBC) - Ray tracing	- Collapsed Cone Convolution (CCC) - Analytical Anisotropic Algorithm (AAA)	- Monte-Carlo (MC) - Acuros XB (AXB)

* Dose calculation algorithms for photon beams in Eclipse TPS:

- *Analytical Anisotropic Algorithm (AAA)*

AAA is based on the 3D collapsed cone superposition technique; AAA uses the superposition of spatially close scattering kernels obtained from Monte Carlo simulation and separates the model for

each primary photon, photon scattering, and secondary electron. The final dose is the total dose from the superposition of photons and electrons.

- *Acuros XB Algorithm (AXB)*

Acuros XB is based on the linear Boltzmann transport equation (LBTE) and directly considers the effects of heterogeneities. Acuros XB provides accuracy equivalent to the Monte Carlo method.

* Correction of heterogeneity density in dose calculation: takes into account changes in electron density and atom number of the environment along the ray tracing, which can be divided into two types: *(1) Correction based on coefficients:* adjust dose distribution according to changes in tissue density; *(2) Model-based correction:* the dose at a point in a heterogeneous medium is calculated directly using a radiation transport model.

All methods are traced from the primary beam. Their differences are mainly in how the contributions of scattered photons and electrons are resolved.

CHAPTER 2. STUDY EQUIPMENT AND METHODS

2.1. Study equipments

- TrueBeam STx linear accelerator: with energy photon beams of 6, 8, 10, 15 MV FF and 6, 10 MV FFF.

- Measuring tools and equipment: ionization chamber CC13, CC04, dosimeter DOSE-1, CCU controller, water phantom IBA Blue, data recording and processing software OmniPro-Accept.

- Heterogeneous density multi-layer phantom: 5 different density layers (tissue equivalent, lung parenchyma, tissue, bone, and tissue equivalent).

- E2E SBRT 036A thoracic phantom: includes many parts with size, structure, and density equivalent to the human body, including a

pseudotumor block and holes for installing an ionization chamber to measure and survey dose.

- Gamma Index method: compares the difference in dose (ΔD) and distance (DTA) between calculated and measured dose distributions. Pairs of points are compared on the recommended acceptable dose/distance criteria, for example, 2%/2mm. The ratio of qualified comparison point pairs to the total number of point pairs is called GPR (Gamma Pass Rate).

2.2. Research methods

Research and evaluate photon beam characteristics and radiotherapy dose calculation algorithms using experimental dosimetry by ionization chamber and Monte Carlo simulation (GATE, PRIMO). The results are evaluated and compared using the Gamma index method.

2.2.1. Measure and survey photon beam characteristics using an ionization chamber

Directly use the linac photon beam to calibrate the CC13 ionization chamber to ensure accuracy in dose measurement.

Different energy photon beams were investigated in the water phantom: 04 FF beams (6, 8, 10, and 15 MV) and 02 FFF beams (6, 10 MV). The results include percentage depth dose curve (PDD), and off-axis distance curve (profile).

2.2.2. Simulate and study photon beam characteristics

- PRIMO and GATE tools are used to simulate the dose distribution of photon beams in a water phantom. The settings were repeated the same as experimental measurements. Simulation results are confirmed compared with experimental measurements (in section 2.2.1) using the Gamma Index.

- Survey and evaluate several photon beam characteristic parameters: max, TPR20/10, surface dose (Ds), dose field size (FS), penumbra, flatness (F), and symmetry (S).

2.2.3. Evaluation of dose calculation algorithms using heterogeneous phantoms

- Measure and survey the dose distribution of photon beams according to depth in the heterogeneity density phantom using a CC13 ionization chamber, field size 10x10cm2, SSD 100cm.

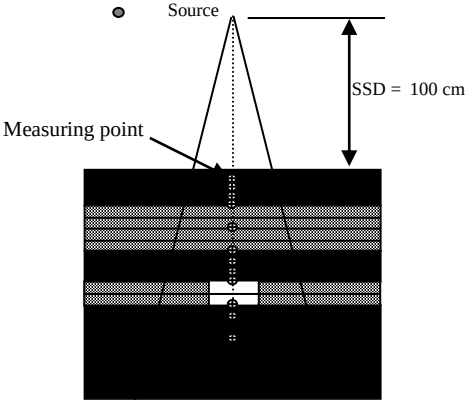


Figure 2.19. Measure dose at depths in the heterogeneity density phantom

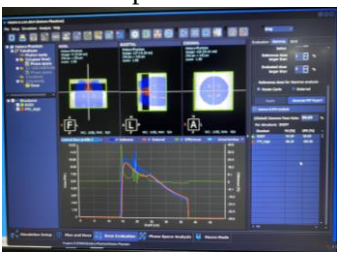


Figure 2.22. Calculate the dose distribution on heterogeneous density phantom using the PRIMO

- Dose distribution planning on heterogeneity phantom with two algorithms, AAA and AXB (only change the algorithm and keep other

setup conditions unchanged). The setup conditions are the same as experimental measurements.

- Simulate dose distribution on heterogeneous phantom using the PRIMO tool; data is taken from planning. The settings are the same as those for measuring and calculating on TPS.

2.2.4. Evaluation of dose calculation algorithms using thoracic phantom E2E

- Calculate dose on E2E phantom using 02 algorithms AAA, AXB.
- Simulate dose distribution on E2E phantom using PRIMO

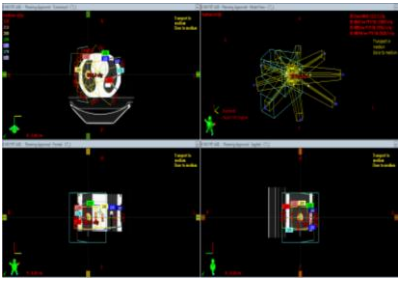


Figure 2.25. Calculate the dose on TPS with the E2E SBRT phantom using different algorithms

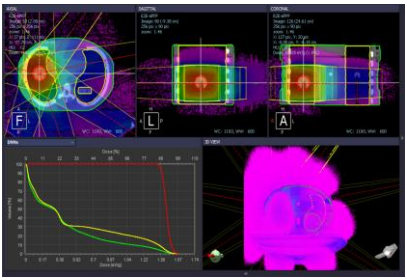


Figure 2.26. Simulation of dose distribution on E2E SBRT phantom using PRIMO with 6 MV FFF photon beam

- Experimental dose distribution measurement on E2E phantom using CC04 ionization chamber. Five measurement locations: tumor center, spinal cord, heart, left lung, left lung-heart junction.

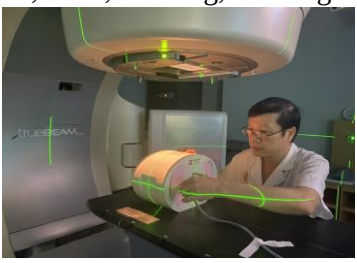


Figure 2.27. Set up the E2E phantom on the linac table to measure the dose

2.2.5. Evaluation of dose calculation algorithms on actual patient radiotherapy plans

16 initially treated lung radiosurgery plans were modified to change from the AAA to AXB algorithm or vice versa. Then, the above plans are simulated using PRIMO. The agreement between simulation and TPS dose calculation is evaluated based on the GPR index, and dose distribution indices at the tumor and normal organs are compared to evaluate the algorithm. The plans between the two algorithms, AAA and AXB, are also analyzed, directly compared, evaluated, and evaluated for the effectiveness of the algorithms.

CHAPTER 3. RESULTS AND DISCUSSION

3.1. Simulation results of photon beam characteristics of the TrueBeam STx linac

3.1.1.Ionization chamber calibrated results with linac photon beams

Table 3.2. Calibration factors of different ionization chambers for different linac photon beam qualities

Investigated Geometry			**Calculated calibration factor** $N_{D,w,Q}$ *(cGy/nC)*	
E (MV)	***SSD (cm)***	***SCD (cm)***	***FC-65G***	***CC13***
6	100		4,83	26,40
		100	4,83	26,40
15	100		4,86	26,60
		100	4,86	26,60

The values of $N_{D,w,Q}$ for the same IC are negligible different, even for two different beam qualities of the MV X-ray LINAC (the biggest difference is about 0.7%). This reveals that the energy responses of IC are identical in a wide range of spectrum averaged energies of MV X-ray LINAC.

3.1.2. Simulation results using PRIMO and GATE in water phantom

3.1.2.1. Simulation results of percentage depth dose (PDD)

- Comparison of GPR index on PDD: With the criterion of 3%/3mm, GATE's GPR is higher than PRIMO; On the contrary, with the criterion of 1%/1mm, the GPR of GATE is lower than that of PRIMO. With the 2%/2 mm criterion, as the American Association for Medical Physics (AAPM) recommended, the GPR of both tools is equivalent, and all values reach above 95%.

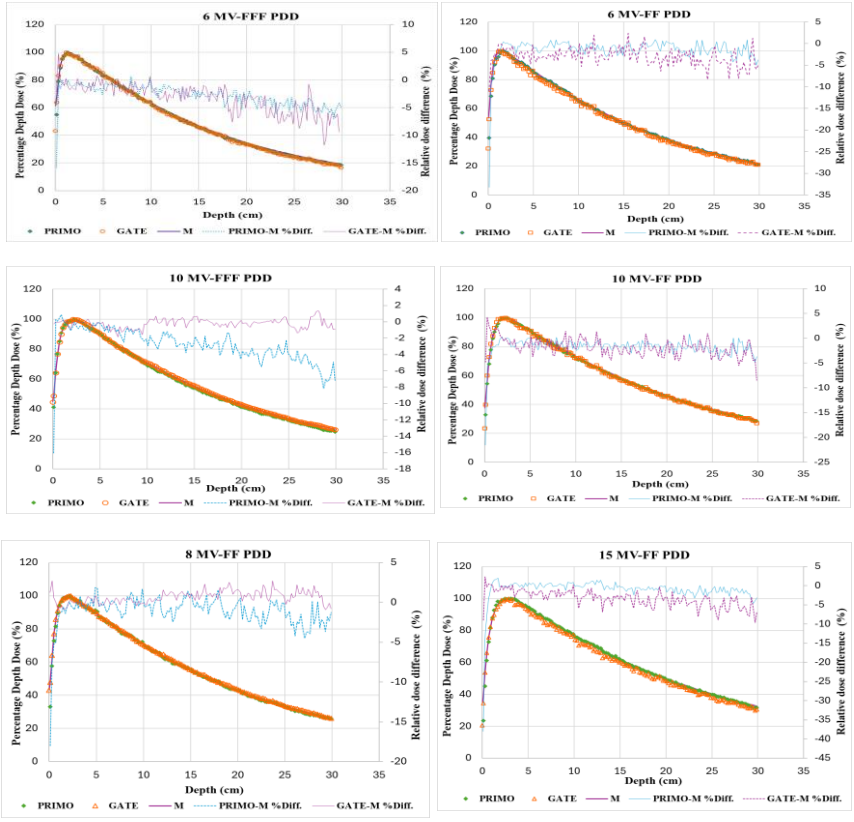


Figure 3.1. PDD simulation results of the TrueBeam STx photon beams on PRIMO and GATE compared to experimental measurements

3.1.2.2. Simulation results of off-axis distance (cross-profile)

- Comparing the GPR index on cross-profile: We can see good agreement between PRIMO and GATE compared to experimental measurements (most GPR >90%). With the criterion of 2%/2mm according to AAPM, GPR is over 95% and 90% for GATE and PRIMO, respectively.

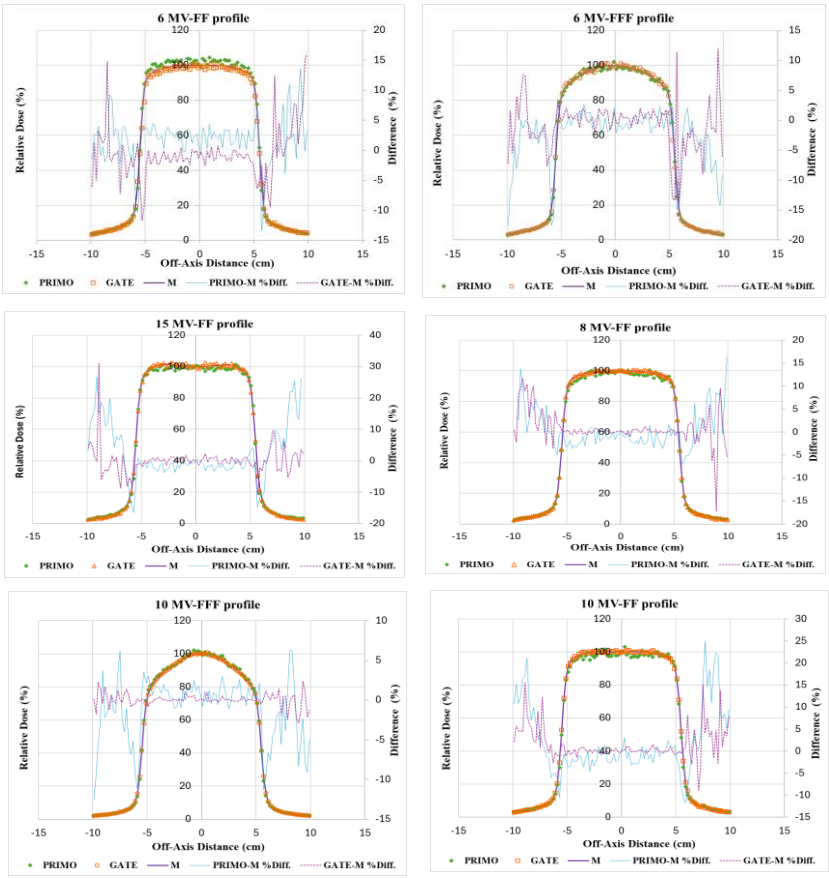


Figure 3.2. Cross-profile simulation results of TrueBeam STx photon beams on PRIMO and GATE compared to measurements

PDD and cross-profile simulation results obtained from GATE show that GPR is significantly higher than PRIMO for all three acceptance criteria (3%/3mm, 2%/2mm, 1%/1mm), except PDD with the criterion of 1%/1mm.

3.1.3. Results of survey and evaluation of photon beam characteristics

- z_{max} and $TPR_{20/10}$: Compared to the experiment, the z_{max} values on PRIMO and GATE simulations differ by about 1-2 mm, within the tolerance; $TPR_{20/10}$ values all have less than 2% discrepancy.

- Surface dose: The majority of surface dose values compared to experimental measurements obtained on GATE have differences more minor than PRIMO for both 1mm and 3mm surface depths, except for the 15 MV FF photon beam.

- Dose field size: There is no significant difference in the survey field size on PRIMO and GATE when compared with experimental measurements. The largest difference recorded is 2 mm, corresponding to 2% of the field size of 10x10cm2. The field size of the FFF photon beam is smaller than the FF in both experiments and simulations, but this difference is not significant.

- Penumbra: Many simulation results of PRIMO and GATE are larger than measurements; On the contrary, the three-photon beams of 6 MV FF and FFF, 10 MV FF on PRIMO have values of the penumbra narrower than the experimental measurements.

- Flatness: all values obtained from simulation are less than 3%. There is no significant difference between PRIMO and GATE simulation results.

- Symmetry: all simulation values are less than 106%, meeting regulatory criteria.

In summary, although there are minor discrepancies in the TrueBeam STx photon beam characteristics simulation results using

both PRIMO and GATE tools compared to experimental measurements, the cause may be due to many factors, such as experimental conditions, uncertainties in measuring equipment, and modeling assumptions in simulations. However, the high agreement observed between simulation and measurement results reaffirms the simulation method's reliability for evaluating radiotherapy accelerators' photon beam characteristics. These results contribute to validating the simulation model and provide confidence in its accuracy for dosimetry assessments in radiotherapy planning.

3.2. Research and evaluate algorithms using heterogeneous density phantom

In this study, a single field was used for each different photon beam. The dose according to depth in the phantom is calculated on TPS (with two algorithms, AAA and AXB) and simulated on PRIMO. Experimental measurements using an ionization chamber along the depth in the phantom on the beam center axis at several points (in a tissue-equivalent environment, tissue-lung parenchyma interface, in lung parenchyma, tissue-bone interface)

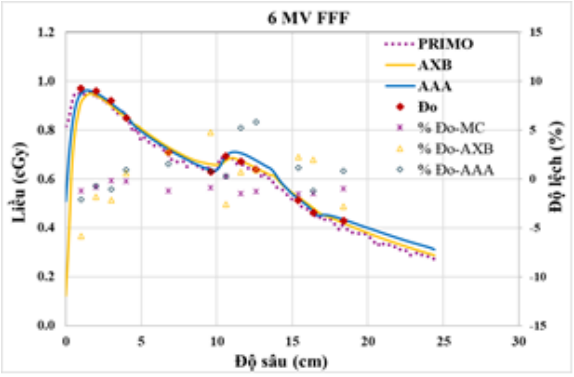


Figure 3.4. Deep dose distribution in heterogeneity density phantom according to planning, simulation, and experimental measurement of 6 MV FFF photon beam

The results show that:

- Dose calculation simulation on PRIMO using the Monte Carlo algorithm gives the value closest to experimental measurements for all surveyed beams.

- Using photon beams of energy 6MV FF and FFF gives dose calculation values closest to experimental measurements and simulations. Higher energy beams ranging from 8, 10, to 15 MV give results with less precision.

- The 6MV FF photon beam gives generally more accurate results than the 6MV FFF beam. On the contrary, the 10 MV FF photon beam gives less accurate calculation results than the 10 MV FFF beam.

- Large discrepancy doses between algorithms are received in material layers equivalent to lungs, bones, and adjacent areas where the environmental density changes considerably. In the lungs, where material density is low, the difference calculated by the AAA algorithm is always more significant than AXB and is often an enormous difference in survey points and beams.

- The calculated values of the algorithms in the lungs are all higher than experimental measurements. At the tissue-equivalent environmental survey point, the transition point between the low-density layer, which is the lung, and the high-density material layer, which is equivalent to the bone, the dose difference value is also quite significant, the values are calculated by the TPS algorithm (AAA, AXB) are mostly higher than experimental measurements.

3.3. Evaluation of dose calculation algorithms using E2E thoracic phantom

3.3.1. Results of dose distribution on E2E phantom

Steps:

- Experimentally measure a number of points at the tumor and critical organs (spinal cord, left lung, heart, left heart-lung junction).

- Calculate the dose on TPS (calculated in AAA, AXB) and simulate it on PRIMO, extracting the dose at points similar to experimental measurements.

In this study, each plan used a specific photon beam, implemented with two different algorithms, a total of 8 irradiated fields; the total delivered dose unit was 1600 MU (200 MU/1 field), and dose distribution on the phantom is significantly different.

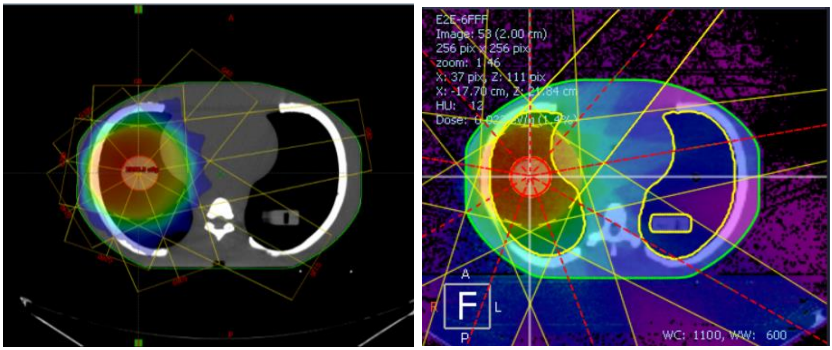


Figure 3.9. Dose distribution on E2E SBRT phantom using Eclipse TPS (left) and PRIMO simulation (right)

The results show that most of the dose values calculated by algorithms AAA, AXB and PRIMO simulation are lower than experimental measurements, PRIMO gives the calculated value closest to experimental measurements.

Compared with the measurement and simulation results, most dose values calculated by the AXB algorithm have more accurate values than AAA ones. The dose distributed to tumors and critical organs of 10MV photon beams (FF and FFF) is higher than 6 MV. Flattened filter photon beam (FF) also gave higher dose values at the survey points than flattened filter-free photon beam (FFF) with both 6 and 10 MV energy levels.

3.3.2. Compare and evaluate algorithms

Overall, the simulation results using the PRIMO tool with the Monte Carlo algorithm give an accuracy value closest to experimental measurements, with the most significant error (2.85%) recorded at the left heart-lung border with the 10 MV FFF photon beam. The dose discrepancy in the left lung was most significant with all three algorithms and all photon beams, and most are smaller than measurements. This measurement point location is entirely inside the lungs, where the density environment has low or low electron density, so algorithm dose calculation is generally hard and less accurate.

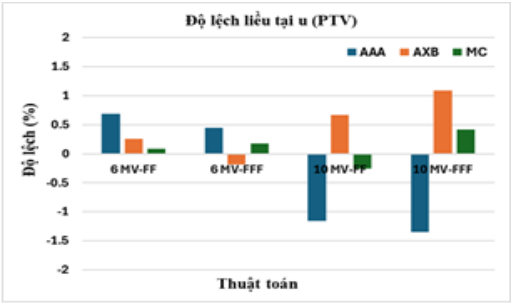
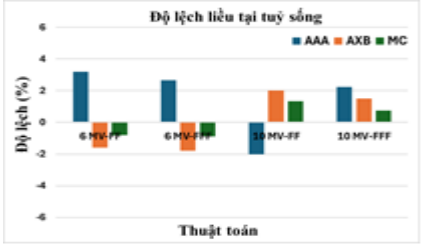
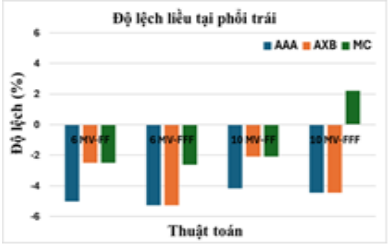


Figure 3.11. Dose difference in tumor (PTV)

The AXB algorithm gives dose calculation results closer to the experimental and simulated measured values than the AAA algorithm. With plans made on the E2E phantom, density changes are as complex as the human body, and setting up multiple irradiated fields in different directions will make dose calculation more challenging to reach and complicated. With these conditions, the AXB algorithm gives more accurate results than AAA.





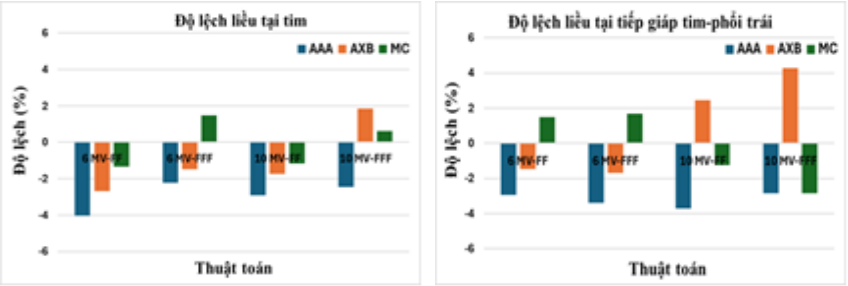


Figure 3.12. Dose difference in critical organs

3.4. Results of research and evaluation of algorithms on actual radiotherapy plans

To have a more detailed assessment of the accuracy of the algorithms, dose calculation and simulation were performed on a group of 16 lung radiosurgery plans that were treated on patients. In which Monte Carlo simulation results are used to compare the two algorithms, AAA and AXB.

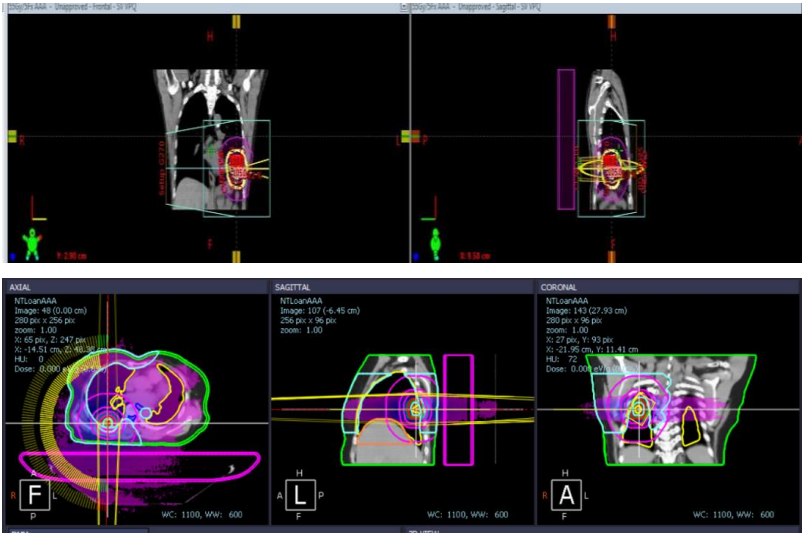


Figure 3.13. Results of lung radiosurgery dose distribution on Eclise TPS (top) and PRIMO simulation (bottom)

3.4.1. Comparison of dose distribution on TPS and PRIMO

- Results of evaluating the agreement between the dose distribution calculated on the planning and simulation: There is good agreement between the dose distribution calculated on the simulation and TPS. With the criterion of 3%/3mm, the received GPR values are all greater than 98%, and many values reach 100%. With the criterion of 2%/2mm, the GPR values of both AAA and AXB algorithms are greater than 95%; the lowest is 95.56% with the AAA algorithm. Most GPR index values calculated using the AXB algorithm are larger than AAA's.

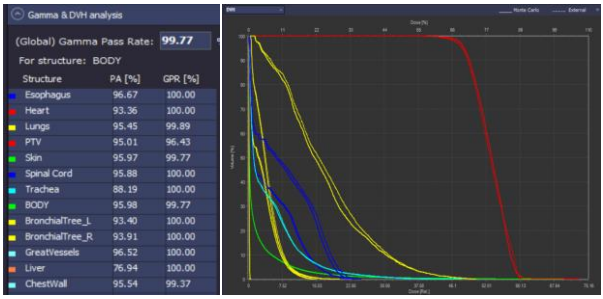


Figure 3.14. Compare planned and simulated dose distributions on dose-volume histogram and GPR index

* Results of dose distribution on tumor (PTV): Compare the results of dose distribution on tumor between two algorithms, AAA, AXB versus Monte Carlo; the indicators of interest are mean dose (Dmean) and maximum dose (Dmax) on tumor volume. Most of the Dmean and Dmax results AXB calculated have more minor differences than AAA. With both algorithms, the Dmean is larger than the simulation; conversely, the Dmax is smaller than the simulation.

* Results of comparing doses to some healthy organs: maximum dose (Dmax) to normal organs were surveyed. Dmax into the spinal cord calculated on AAA is not significantly larger than on AXB; There was no significant difference in cardiac and esophageal Dmax between the two algorithms. Compared to the simulation, the difference in the

Dmax dose of the heart and esophagus is quite significant, less than 5% for the heart, but the difference is up to 8.66% for the esophagus.

3.4.2. Evaluation of AAA and AXB algorithms on treatment planning

The dose distribution indicators on tumors and doses to normal organs are surveyed to evaluate the accuracy and efficiency in calculating dose distribution of the two algorithms AAA and AXB of Eclipse TPS. The 16 lung radiosurgery plans above were surveyed and compared. The statistical method Wilcoxon-Signed Rank test (SPSS v26.0) was used to process data for this research purpose; statistical significance was assessed by p-value < 0.05.

- Evaluate and compare dose distribution indices on the tumor: results show that dose Conformity Index - CI (according to Paddick and RTOG), Homogeneity Index - HI (RTOG), maximum dose on the PTV, Coverage Index - Q, the D2cm (%) and V105% (%) are the dose fall level greater than 100% outside the PTV between the two algorithms AAA and AXB are equivalent, the fluctuation amplitude small statistical dynamic. The two indices, GM (Gradient Measure) and GI (Gradient Index), representing the dose reduction to healthy tissues around the treatment volume, have significant differences. AXB gives values of GI and GM closer to the ideal value than AAA. According to the two algorithms, on the PTV, the mean dose (D_{mean}) is higher with AAA, and maximum dose (D_{max}) were not significantly different.

- Evaluate and compare doses to critical organs: According to the two algorithms, all maximum dose values in normal organs are much lower than the tolerance dose of each organ. Normal lung doses V5 (%), V10 (%), and V20 (%) calculated by AXB were not significantly higher compared to AAA. The mean dose on lung and PTV following the AXB algorithm increased by 4.2% and 1.3%, respectively, but

were not statistically significant. The dose to healthy organs of the two algorithms, AAA and AXB, does not significantly differ.

CONCLUSIONS

1. Main results of the thesis

1. Results of evaluating the suitability of Monte Carlo PRIMO and GATE simulations for the photon beam physical characteristic of the TrueBeam STx linac, with six photon beams including 6 MV FF and FFF, 10 MV FF and FFF, 8 MV FF, and 15 MV FF show:

- There is good agreement between simulation results by both tools and experimental measurements. With the criterion of 2%/2mm, all GPR comparison indexes are >90% according to AMMP REPORT No.85 recommendation.

- There is a high agreement between the PRIMO, GATE simulation results and measurements for the physical characteristic, such as z_{max}, $TPR_{20/10}$, surface dose, dose field size, penumbra, flatness, and symmetry.

2. Evaluation results of AAA and AXB dose calculation algorithms:

- Research on dose distribution in heterogeneous phantoms of photon beams using PRIMO and calculation of TPS using two algorithms, AAA and AXB. The results show that: In the lungs, where material density is low, the dose difference of the AAA algorithm is always larger than AXB and is often the most significant discrepancy in survey points and beams. Significant dose differences are observed in lungs, bones, and junctions, where environmental density changes rapidly. The low energy photon beams, 6MV, give a dose calculation value closest to experimental and simulated measurements compared to higher energy, 8 to 15 MV. Dose on PRIMO simulation using the Monte Carlo algorithm gives values closest to experimental measurements for all used beams.

- Research and evaluate two dose calculation algorithms using a treatment planning system, PRIMO simulation, and measurements on E2E thoracic phantom with four beams of 6 and 10 MV (FF and FFF). The results show that: Compared with the measurement and simulation results, most dose values calculated by the AXB algorithm are more accurate than AAA ones; most dose values calculated by algorithms AAA, AXB and PRIMO simulation are lower than experimental measurements; PRIMO gives the value calculated most closely to experimental measurements among the three algorithms. The dose distributed to tumors and critical organs of a 10MV photon beam is higher than 6MV. The FF photon beam also gives a higher dose distribution than the FFF beam, with energy of 6 and 10 MV.

- Studied and evaluated the dose calculation algorithms on 16 lung radiosurgery plans of actual patients, using the PRIMO tool, the results showed that the dose calculated by the AXB algorithm had a smaller difference than AAA. Directed comparison on radiotherapy plans, most of dose distribution indices on the tumor and critical organs calculated by AXB and AAA showed equivalent results; However, dose calculation according to AXB has D_{mean} on toumor and GI, GM indicators, the dose reduction indexes, that are closer to ideal than AAA.

2. The main contributions of the thesis

The results of the thesis have confirmed the ability to apply Monte Carlo simulation calculation tools such as GATE/Geant4, and PRIMO to serve in clinical radiotherapy as well as in research in Vietnam today, providing medical physicists in Vietnam with necessary information about the characteristics of photon beams on the new generation of linac, their applications, and effectiveness in radiotherapy practice.

The thesis results have enriched the data, increasing the basis for

choosing the optimal dose calculation algorithm in calculating radiation therapy dose distribution, especially in areas with heterogeneous tissue density as large as the chest area.

In addition, the simulation results of photon beams of the TrueBeam STx linac can be used as an input database for further research on radiotherapy (quality assurance plans, radiotherapy techniques, prediction of dose distribution results in cases experimental measurements can not, evaluation of dose distribution on patients that cannot do it...), radiobiology, and radiation safety using the Monte Carlo simulation tool.

3. Limitations and future research directions

The limitation of this thesis is that the evaluation was only conducted according to Monte Carlo simulation and experimental measurements using an ionization chamber. However, other experimental measurement methods have not yet been performed, such as EBT film, thermo-fluorescence dosimeter, and optical photoluminescence.

The next orientation could be to expand the research, using more experimental measurement tools with sufficient accuracy that have been tested in practice.

RECOMMENDATION

Continue to use the photon beam simulation results of the TrueBeam STx accelerator to further research modern radiotherapy techniques, and applications in quality control and quality assurance on radiotherapy, using research on radiobiology, especially biological effects at the cellular level, and research applications to ensure radiation safety.

LIST OF PUBLISHED WORKS

1. Pham Hong Lam, Phan Tien Dung, Le Thi Hoang Anh, Pham Quang Trung, *Photon beam modeling: A comparative study of PRIMO and GATE simulation toolkits for the TrueBeam STx linac*. Nuclear Technology & Radiation Protection. Vol. 39, No. 1 (2024), pp. 58-65, ISI. DOI: 10.2298/NTRP2401058P
2. Pham Hong Lam, Phan Tien Dung, Pham Quang Trung, *Characterizing Photon Beam Properties of a TrueBeam STx Linear Accelerator: An Evaluation of Geant4/GATE Monte Carlo Simulation Tool Performance*. Atom Indonesia, Vol. 41 No. xxx, 2024, 50(3). ISI. DOI: 10.55981/aij.2024.1451
3. Pham Hong Lam, Phan Tien Dung, Hoang Huu Thai, Nguyen Tung Lam, Nguyen Duong Tu, Nguyen Thi Van Anh, Pham Quang Trung. *Comparison of Skin Dose of Flattening Filter and Flattening Filter-Free Beam in Volumetric Modulated ARC Therapy Treatment Plan for Head and Neck Cancer*. 2023 1st International Conference on Health Science and Technology (ICHST); 2023: IEEE.
   DOI: 10.1109/ICHST59286.2023.10565365
4. Pham Hong Lam, Phan Tien Dung, Vu Phuong Quy, Pham Quang Trung, *Evaluation and Comparison of AAA and AXB Dose Calculation Algorithms for Lung SBRT on TrueBeam STx with Eclipse 13.6*, Nucl. Sci. and Tech., Vol.14, No. 1 (2024), pp. 07-19. DOI: 10.53747/nst.v14i1.465
5. Pham Hong Lam, Nguyen Thi Van Anh, Pham Quang Trung, *Evaluate dose distrubution of IMRT and VMAT technique in radiotherapy for head and neck cancer using TrueBeam STx linear accelerator*. Journal of Military Pharmaco-medicine, Vol 44, N°1 (2019), pp. 180-187.
6. Pham Hong Lam, Hoang Thanh Phi Hung, Jin Sunjun, Bui Duy Linh, Nguyen Tuan Khai, Bui Van Loat, Le Tuan Anh, Nguyen Huu Quyet, Pham Duc Khue, Phan Viet Cuong, Phan Tien Dung, Pham Quang Trung, Tran Hoai Nam, Le Ngoc Thiem. *Calibration of ionization chamber in megavoltage X-ray field of medical linear accelerator.* Nuclear Technology & Radiation Protection. ISI. *(accepted).*