Evaluation of the Total Body Irradiation Treatment Planning Using Eclipse

by

Qi Zeng

The Department of
Duke Kunshan and Duke University
Medical Physics Program

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David Huang

Thesis submitted in partial fulfillment of
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ABSTRACT

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Abstract

Purpose: Total Body Irradiation (TBI) is typically performed at extended source-to-skin distance (SSD), and the treatment planning is done by simple point dose calculation based on measurement data. The goal of this study is to validate the use of a computerized treatment planning system (TPS, Eclipse) in TBI planning. Typical TPS is commissioned with beam data collected at standard SSD of 100 cm. Extrapolation is required when planning treatments at extended SSDs beyond 400 cm. This requires comprehensive validation.

Methods: Rectangular water phantoms of different sizes were created in Eclipse. Various dosimetric factors including absolute output at extended SAD, phantom scatter factors, off-axis ratios, TMRs, spoiler factors, and compensator transmission factors were calculated in Eclipse using Analytical Anisotropic Algorithm (AAA, V10) and compared with the TBI commissioning measurements at the same geometry. Homogeneous patient phantoms approximating patient body sizes were created with MATLAB and imported into Eclipse. Dose distributions were calculated in Eclipse, and representative point doses were compared with measurements obtained during treatment and those from standard manual calculation.

Results: Dosimetric factors calculated in Eclipse showed good agreement with TBI commissioning measurements. The differences were all within 2% in the range of clinical situations, with most of them within 1%. When comparing *in vivo* dose measurements and Eclipse calculations, umbilicus (central axis) dose showed better agreement than lung. Along the midline, doses at head and umbilicus agreed better with prescribed dose than doses at neck, lung, and lower legs.

Conclusion: This work demonstrates that Eclipse can be used for TBI planning at extended SSD with beam data from standard SSD. The Eclipse provides not only dose at certain points, but also full 3D dose distributions that allow more detailed evaluation of the patient treatment plan, hence reducing the need for time-consuming *in vivo* dose measurements.

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1. Introduction

Total body irradiation (TBI) is a treatment method that delivers dose to the patients' whole body. TBI is usually used to treat leukemias, lymphomas, and myelomas.[1] It serves to destroy or suppress the patient's immune system and malignant cells before receiving a bone marrow transplant.[2,3] In other words, total body irradiation eliminates the residual cancer cells, helps the body make room for new and healthy bone marrow cells, and reduces the probability of the body rejecting the transplant.[1,2,3] Nowadays, the treatment regimen usually starts with chemotherapy before TBI and bone marrow transplant.[2,3]

The target volume of total body irradiation is the patient's entire body. The goal of TBI is to deliver a uniform dose to the target volume.[4] TG-17 report recommends that the overall accuracy in dose delivery should be within ± 10% in the patients' bodies.[5] Generally, dose is specified at a point midline at the umbilicus.[4] However, the patients' bodies are not uniform and do not have flat surfaces nor same thicknesses. There would be higher dose deposition at thinner body parts, such as head, neck, and lower leg due to less attenuation, which means that those parts would receive higher dose than prescribed.[4] Moreover, the dose deposits more if the density of tissue is lower.[6] In particular, lung has low density, ranging from 0.19 to 0.35 g/cm^3.[7] And lung is one of the most important tissue, which is more sensitive to radiation and has low dose tolerance.[6] For those reasons, lung dose should be limited. In order to reduce the dose at the thinner body sections and the lung part and increase the dose uniformity, physical compensators are commonly used in total body irradiation.[4]

Nowadays, linear accelerators are commonly used for radiotherapy.[4] They have also been used in total body irradiation techniques.[4] Beam energy is a factor in dose uniformity – higher beam energies result in more uniform dose distributions.[5] However, high energy affects the radiation workload and shielding cost. Therefore, considering the maximum acceptable patient size and source to surface distance (SSD), 6 MV is recommended for opposed bilateral fields.[4] If the patient's thickness is more than 35 cm, higher beam energy should be used for better dose uniformity.[4]

Total body irradiation is a special procedure because it requires to deliver the dose to the entire body. The maximum collimator field size is 40 cm by 40 cm. However, the length of the patient's body is usually more than 1 meter. It is challenging to make such large field. Currently, there are several methods to treat TBI patients. The first is to use a large field to treat TBI patients.[8] The treatment is performed at extended SSD, usually more than 4 meters, in order to cover the patient's whole body in one field. The gantry angle is tilted about 90 or 270 degree to create horizontal beams. Thus, it is required that treatment room for total body irradiation is larger than normal treatment room. An anteroposterior (AP)/posteroanterior (PA) or opposed bilateral fields are used for this method. Patient seat on the couch in a semi-fetal position or lie on the couch with knee bending with bilateral opposed fields.[4,8] Or patient is treated in AP/PA parallel opposed field with standing position.[2] Another treatment method is using multiple adjacent small fields. Some centers have developed methods using CT-based 3D planning, intensity-modulated radiation therapy (IMRT), and inverse planning to improve dose uniformity.[9] For example, Tyson *et al*. used a succession of small fields and electronic compensation technique with treatment planning system to deliver uniform dose.[10]

AAPM TG-17 provides techniques and calculation for total body irradiation, which is based on the basic physical principle.[5] Currently, there is no commercial treatment planning system designed specifically for total body irradiation.[11] At Duke University Medical Center, the treatment planning is done by simple point dose calculation based on measurement data, which is called reference points. Those reference points are along the patient's body and are specified at the centers of some significant body parts, such as head, neck, lung, umbilicus, and lower legs. The dose calculation follows the prescription, giving the prescription dose at those certain points. However, via the calculation, we can only know the dose at reference points. It is difficult to know the dose distribution and whether the doses are uniform within ±10% in patient's body. Therefore, the aim of this work is to validate the use of a computerized treatment planning system to calculate the dose distribution for total body irradiation planning.

Total body irradiation is a special treatment procedure. Not only it delivers dose to the patient's whole body, but also it requires extended SSDs for a large field. For typical treatment planning system, Varian Eclipse for example, it is designed for the standard treatment modalities, such as 3D conformal radiotherapy, IMRT and VMAT.[12] Those treatment are all performed at standard SAD of 100 cm. In addition, treatment planning systems are commissioned with beam data collected at standard SSD. For total body irradiation, the treatments are performed at extended SSD. Whether treatment planning system can calculate dose at extended SSDs beyond 400 cm is a challenge. Thus, the first step is commissioning. The commissioning test in treatment planning system is to verify that whether Eclipse can produce the same factors values as the TBI Databook at extended SSDs by using same geometry, which is the standard data that measured during the TBI commissioning. After the commissioning test, treatment planning system are tested for calculating the dose distribution and the results are compared with the *in vivo* dose measurement and the calculation method that developed by Duke University Medical Center radiation oncology department.

2. Total Body Irradiation Treatment Process at Duke University Medical Center

At Duke University Medical Center, there are two types of total body irradiation treatments: treatment with and without lung dose limits. Whether patients are treated with or without lung dose limits is dependent on patient's disease and physician's treatment plans. Patients without lung dose limits are treated with 200 cGy in 1 fraction. However, when patient receive multiple fractions, their lung needs to be protected. Adult patients are usually treated with 150 cGy per fraction for 9 fractions and pediatric patients receive 165 cGy each fraction for 8 fractions. Generally, patients receive 2 fractions per day, one in the morning and one in the afternoon. The treatment usually starts on Monday or Tuesday morning to ensure the treatment is completed by Friday. The absorbed dose rate is 5-20 cGy/min in order to reduce toxicity to late responding tissues.[13,14]

2.1 Clinical Setup for Total Body Irradiation Patients

Patients are treated either in standing position or supine position, depending on the condition of patients (stamina) and the preferences in different hospitals. For the standing position, patients would receive the dose from two fields, AP (anterior-posterior) and PA (posterior-anterior). For the supine position, patients lie on a couch that is specially designed for total body irradiation and receive the dose from opposed bilateral fields.[5] Usually, a patient is first treated using one field in a specific position and then treated in another position with a different field. Therapists enter the treatment room with the radiation switched off to change the patient's position after the first field has been delivered. Duke University Medical Center uses supine position because most TBI patients are too weak to stand for more than 10 minutes. It is also easier to set up the supine position with two parallel opposed lateral fields than standing position with AP/PA fields, thus saving time.

Total body irradiation treatment requires a large treatment room because patients are treated at source to patient midline point distances (SPD), which are 400 cm for TBRed machine and 475 cm for NovalisBlue machine at Duke University Medical Center. Due to the limitation of treatment room space, the gantry has to be tilted to about 90 or 270 degrees to achieve an SPD above 400 cm. Collimator field size is set to 40×40 cm^2 (defined at 100 cm SAD) with collimator angle of 0 degrees, which can accommodate patients in a bent knee position. The isocenter is at the midpoint of patients' umbilicus.

Physical compensators are commonly used in order to increase the dose uniformity, which compensate for the thinner parts of the body during the treatment.[4] At Duke University Medical Center, physical compensators are made of brass. The thickness of one piece of compensator is 1 mm. The transmission factor is about 0.968 for each compensator. The number of compensators in different areas of the body is adjusted based on the thickness of that area. Usually, the compensators are applied on lung and the thin body parts, such as head, neck, and lower legs. The thinner the area compared to the thickness of patient's umbilicus, the more compensators are used to reduce the dose to that part and increase the whole body's dose uniformity.

In addition, higher photon beam energies reduce the dose delivered to the superficial structure.[5] Thus, to deliver a homogenous dose to patients, a spoiler is usually used during treatment to degrade skin sparing and increase skin dose to at least 90% of prescribed dose.[4] It is placed between the linear accelerator (Linac) head and the patient's body, usually away from the patient's body at about 1.5 meters. The spoiler is made of 0.5 inches acrylic or polycarbonate.

Before designing a treatment plan for a patient, patient body sizes of different areas, including the head, neck, shoulder, mid-mediastinum, umbilicus, pelvis, upper leg, knee, and ankle, are measured using calipers for further TBI treatment calculations (shown as Figure 1). In addition, if patients are treated with a lung dose limit, they are required to do a chest x-ray in order to determine the lung size for further dose calculation. After acquiring measured data, TBI treatment plans are designed for the patients. Because there are two Linac machines used for total body irradiation, two treatment plans for these two machines are created, in case one machine malfunctions. A program named *TBI Calc* has been developed by the Duke Radiation Oncology department. "TBI Calc" is used to calculate total body irradiation and design treatment plans for patients. The program is based on simple point dose calculation. The results of the program can be verified by hand calculations. Hand calculations for total body irradiation will be explained further in the next section.

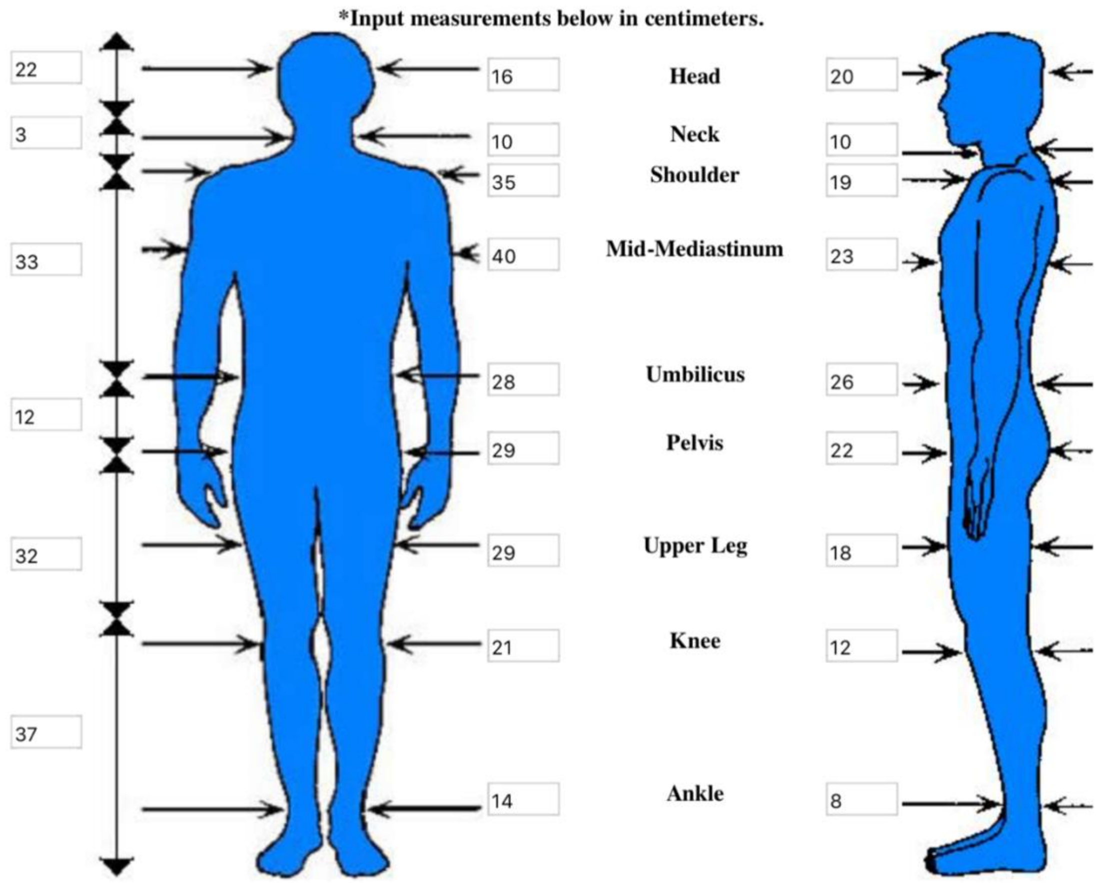

Figure 1: An example of patient's dimensions data that measured before treatment planning.

Some patients may gain weight or lose weight due to the disease and other complications.[16] Before the first treatment, therefore, medical physicists use calipers to measure the thickness of patient's umbilicus again to check if the thickness is within the acceptable body weight fluctuation. If the thickness of umbilicus exceeds the acceptable range, treatment plans need to be redesigned.

When patients lie down on the couch with their knees bending, their arms are required to be positioned on the chest for lung protection. Then, therapists shift the couch to align the patient's sagittal axis with the laser in the treatment room. When the setup is completed, the gantry is rotated to about 270 degrees; the light source is switched on; then the tray is placed on the Linac head. Therapists adjust the position of compensators on the tray based on the light coming from the Linac head. The shadow of the compensator on the patient's body can help therapists to adjust the position of compensator.

Lung is a critical structure and needs to be protected. Therefore, a computed radiography (CR) film is applied to check the position of the lung compensator in order to verify good lung coverage. The CR film is placed on the patient's side that is nearer the wall. Thus, the radiation that comes from the Linac head and passes through the patient's body and lung parts is recorded by the CR film. Before the actual treatment, the beam is switched on for a short period of time. Thereafter, the therapists enter the treatment room again to retrieve the CR film. After the CR film is read out, the lung coverage should be checked by the physician.

Optically Stimulated Luminescent Dosimeter (OSLD) is utilized for the *in vivo* dose measurement. Two OSLDs are taped together and placed under 1 cm bolus. The purpose of bolus is to avoid measuring the dose at build-up region.[5] Then they are placed at the patient's twist. If the patient has lung dose limit, dose at the lung part should be measured as well, placing two OSLDs on the patient's arm on the same side as the twist. The OSLDs placed on the arm measure the lung dose. And the OLSDs placed on the twist to measure the umbilicus dose. OSLDs record the entrance and exit dose of lung and umbilicus. The midplane doses are estimated as the mean of the entrance dose and the exit dose.[17] After the first treatment, OSLDs are read out by the dose reader machine. The reading is compared with the prescription dose and limited dose. If the reading exceeds $\pm$10% of the prescription dose or dose limit, it should be reported, and the treatment plans need to be adjusted for the further treatment.

2.2 Hand Calculation for Total Body Irradiation

The "TBI Calc'' is based on the simple point dose calculation, which applies basic dose calculation principle. After measuring the patient's thickness in different areas, patient equivalent square can be calculated by the equation

$$Patient\ Eq.Sq = \frac{2ab}{a+b}$$

where a is the height of patient's whole body, and b is the average anterior to posterior separations in different body parts because it uses bilateral opposed fields.

The prescription dose is specified at the umbilicus.[5] The further calculations for the head, neck, lung and low legs are based on the calculations at umbilicus. The equations to calculate the monitor unit (MU) and dose rate for the machine are

$$MU = \frac{0.5 \cdot (Prescription\ Dose)}{(MachineOutputFactor) \cdot (TPR) \cdot (ScatterCorrection) \cdot (TrayFactor) \cdot (SpoilerFactor)}$$

$$Dose\ Rate\ \left[\frac{cGy}{min}\right] = \frac{0.5 \cdot (Prescription\ Dose) \cdot (Machine\ Dose\ Rate)}{MU}$$

The prescription dose is 150 cGy for adult patient and 165 cGy for pediatric patient. The machine output factor is 0.0498 cGy/MU for the NovalisBlue machine and 0.682 cGy/MU for the TBRed machine. TPR (tissue-phantom ratio) and scatter correction (scatter factor) are measured when machine commissioning for total body irradiation. The values of TPR and scatter factors implemented for the MU calculation are interpolated in terms of the field size and treatment depth.

The dose is prescribed at the midpoint at the level of umbilicus and some reference points inside the body, such as head, neck, lung, and lower legs. Thus, in order to keep the same doses along the midline as the prescribed dose, the number of compensator pieces to the head, neck, lung and low legs should be calculated. The equivalent square of various areas is calculated by the same equation as the patient equivalent square. For example, head equivalent square is

$$Head\ Eq.Sq = \frac{2 \cdot Head\ Height \cdot Head\ Width}{Head\ Height + Head\ Width}$$

Because head is thinner than the umbilicus, the dose to the head should be reduced in order to acquire better dose uniformity. Thus, the MU to the head is acquire according to the equation below

$$MU\ to\ the\ Head = \frac{TPR@Umbilicus}{(TPR@Head) \cdot OAF}$$

where $TPR@Umbilicus$ can be obtained from the TBI Databook by calculating the head equivalent square and the depth of surface to the head midline. OAF is off-axis factor, which related to off-axis distance and depth. OAF of head also can be obtained from the TBI Databook by measuring the distance of center of umbilicus to center of head.

However, during the treatment, the MU is delivered to the patient's whole body, which means the MU to the head is the same as the MU to the umbilicus. Thus, the compensators for the head are used to reduce the dose per monitor unit to the head. The reduction of dose to the head can be presented as

$$Reduction = \frac{MU\ to\ the\ Head}{MU}$$

After calculating the reduction of head, the number pieces of compensator can be acquired by matching the value of reduction and the value of transmission factor in the TBI Databook.

The calculation process for the neck and lower leg is the same as the calculation for the head. However, due to the scatter from the head and the rest part of the body, it is assumed that the neck would receive more radiation. Therefore, the neck equivalent square is larger than the normal equivalent square when doing the calculation. The equation for the neck equivalent square is

$$Neck\ Eq.Sq = \frac{1.5 \cdot 2 \cdot Neck\ Height \cdot Neck\ Width}{Neck\ Height + Neck\ Width}$$

For the patients who need to protect the lung, there is lung dose limit that should be consider when calculating mutually. Therefore, the MU to the lung part is calculated by the equation below

$$MU\ to\ Lung = \frac{TPR@Umbilicus \cdot Max\ Lung\ Dose}{TPR@Lung \cdot OAF \cdot Prescribed\ Dose}$$

where $Max\ Lung\ Dose$ is the lung dose limit, the lung dose limit is usually 1000 cGy or 800 cGy for total fractions based on the physician's prescription. $TPR@Lung$ is the TPR that relating to the equivalent square of lung and depth of the surface to the lung. OAF is the off-axis factor in terms of the distance from the lung center to the umbilicus. Prescribed dose is the total dose delivered to the whole body, 1350 cGy for the adults, 1320 cGy for the pediatric, 200 cGy for the patients without lung dose limits. The number of compensators for the lung part is obtained by calculating the reduction of the lung and matching the value of the reduction with the transmission factor in the TBI Databook.

After calculating the MUs for the patient's whole body, MUs are needed to be corrected based on the patients' thickness. Some patients' bodies sizes are big so that the value of MU is large. The dose to the surface is much higher than the dose in the center of the body, which is beyond $\pm$10% dose uniformity. Thus, MUs need to be reduced to decrease the surface dose according to the patients' body sizes. In contrast, if the patient's size is too slim or patients are pediatric, the MUs are corrected to increase the surface dose to make the dose distribution more uniform. In the actual treatment, corrected MUs are implemented instead of uncorrected MUs.

"TBI Calc" program calculates the uncorrected and corrected MUs to the patient's entire body, dose rate, the number of the compensators for the thinner body parts and the dose rates during the treatment. "TBI Calc" and treatment planning system (Eclipse) are two independent systems. Thus, when the treatment plans are finished by the "TBI Calc", the parameters including the corrected MUs and dose rate would be input to the treatment planning system. Once the plans are approved, patients would be treated following the plans.

3. Commissioning of Treatment Planning System for TBI

3.1 Introduction

Before the machines are used, the commissioning test is the critical procedure to confirm that the dose algorithms in the treatment planning system can reproduce the same result as the measured dose.[18] Total body irradiation is a special procedure, no commercial treatment planning system is specifically designed for it.[11] Therefore, it is vital to verify if the treatment planning system can be used to calculate dose for total body irradiation at extended SSD.

The treatment planning system that we used for this work is Varian Eclipse planning system (Analytical Anisotropic Algorithm (AAA), version 10.0). Varian Eclipse External beam mode is designed for the standard treatment modalities, such as 3D conformal radiotherapy (3DCRT), intensity modulated radiation therapy (IMRT), and volumetric modulated arc therapy (VMAT).[12] The commission data in the treatment planning system is only confirmed in the standard situation, for example 100 cm SAD. The extended treatment distance, such as 400 cm source-to-patient midline distance (SPD) for the total body irradiation, is rarely used in treatment planning system. Thus, extrapolation of commissioning data is required when planning treatment that use extended SSDs above 400cm; this demands comprehensive validation. To date, there has been no research performed to commission Eclipse for TBI treatment planning. Thus, the commissioning test for the total body irradiation is necessary in the treatment planning system (Eclipse) before it used to calculate the patient's body dose distribution.

To this end, rectangular water phantoms of different sizes were created in Eclipse. Various dosimetric factors, including absolute output at extended SAD, phantom scatter factors, off-axis ratios, Tissue maximum ratios (TMRs), spoiler factors, and compensators transmission factors were calculated in Eclipse at the same geometry as TBI Databook. TBI Databook is the standard data that was collected at standard SSD of 100 cm in the machine commissioning process for total body irradiation. Then the results that calculated in the treatment planning system were compared with the TBI Databook. Overall, the commissioning tests in the treatment planning system are to verify these factors in the same condition as the clinical commissioning for total body irradiation.

In addition, we investigated the influence of patient's body size on the dose distribution. In general, the surface dose would increase for thick areas in order to achieve the prescribed dose at the reference points: head, neck, lung, umbilicus and lower legs.[5] The surface dose may exceed 110% of the prescription dose, which is not desirable in TBI treatment planning. In order to explore the relationship between the patient sizes and the dose uniformity, the dose profiles along 3 axes (from left to right, from superior to inferior, and anterior to posterior that all cross the center) with various thicknesses phantoms are calculated in Eclipse.

3.2 Methods

3.2.1 Output

For total body irradiation, output is the dose rate that machine delivered at source-to-patient midline distance (SPD). The SPD is 475 cm for the NovalisBlue Machine and 400 cm for the TBRed machine. Output was measured using a large water-equivalent phantom and at the 1.5 cm depth during commissioning. In the Varian Eclipse treatment planning system, output should be calculated in the same condition, which is at 475 cm SPD and 1.5 cm depth. Due to the limits of dose calculation algorithm, the dose directly calculated at the 1.5 cm depth is assumed to be inaccurate. Therefore, the doses at 10 cm depth were calculated instead in the Eclipse, then converted to the dose at 1.5 cm depth on the basis of the inverse square law and PDD or TMR conversion.

In order to verify that output follows the inverse square law in the Eclipse, the outputs were calculated at difference distances, such as 100 cm SSD, 200 cm SPD, 300 cm SPD, 400 cm SPD, and 475 cm SPD (for the NovalisBlue machine only) individually. A 30×30×30 cm^3 water equivalent phantom was created in the Eclipse for the output verification. The calibration is usually at the 100 cm SSD and 1.5 cm depth and 10×10 cm^2 field size in commissioning and annual QA. In Eclipse, for the calibration condition (shown in Figure 2), the dose was calculated at 100 cm SSD and at 10 cm depth, then the dose was converted to the dose at 1.5 cm depth by implementing the equation below.

$$D(d = 1.5cm, SSD = 100cm, FS = 10 \times 10cm^2) = \frac{D(d = 10cm, SSD = 100cm, FS = 10 \times 10cm^2)}{PDD(d = 10cm, SSD = 100cm, FS = 10 \times 10cm^2)}$$

where PDD is the percent depth dose, obtained from the TBI Databook. The value of $PDD(d = 10cm, SSD = 100cm, FS = 10 \times 10cm^2)$ is 0.669 for the NovalisBlue machine and 0.664 for the TBRed machine.

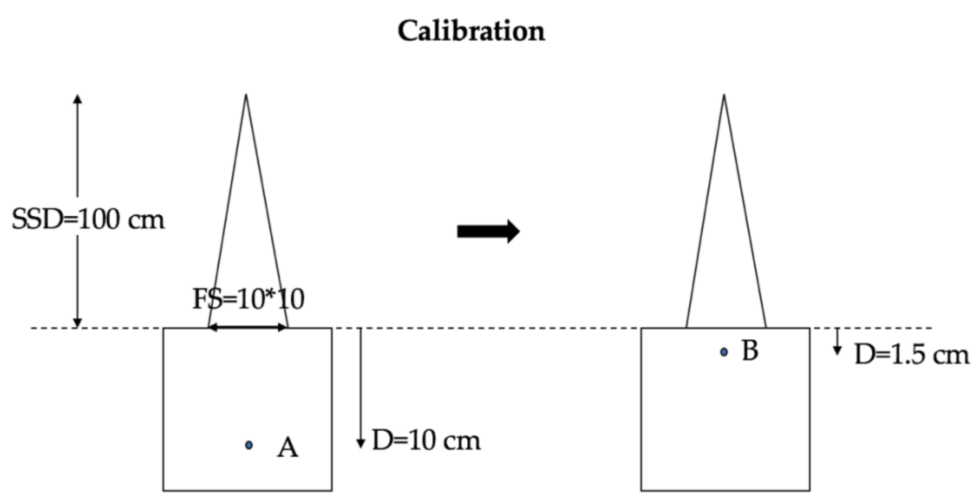

Figure 2: Output calibration at 100cm SSD. In Eclipse, the dose is calculated at point A, 10 cm depth. Then convert it to the dose at point B, 1.5 cm depth.

For the various SPDs, the doses were calculated at 200 cm, 300 cm, 400 cm, and 475 cm SPD respectively and 10 cm depth with 40×40 cm^2 collimator field sizes, then converted it to the doses at the 1.5 cm depth as well for the same reason (shown in figure 3). The equation of derivation is

$$D(d = 1.5cm, SPD, FS = 40 \times 40cm^2)$$

$$= \frac{D(d = 10cm, SPD, FS = 40 \times 40cm^2)}{TMR(d = 10cm, FS = 40 \times 40cm^2)} \times \left(\frac{SPD + 8.5}{SPD}\right)^2$$

where SPD is 200 cm, 300 cm, 400 cm, and 475 cm, respectively. $TMR(d = 10cm, FS = 40 \times 40cm^2)$ was acquired from the TBI Databook, the value is 0.833 and 0.830 for the NovalisBlue machine and the TBRed machine, respectively. $\left(\frac{SPD+8.5}{SPD}\right)^2$ is the component of the inverse square law, 8.5 cm is the distance from the 10 cm to the 1.5 cm depth.

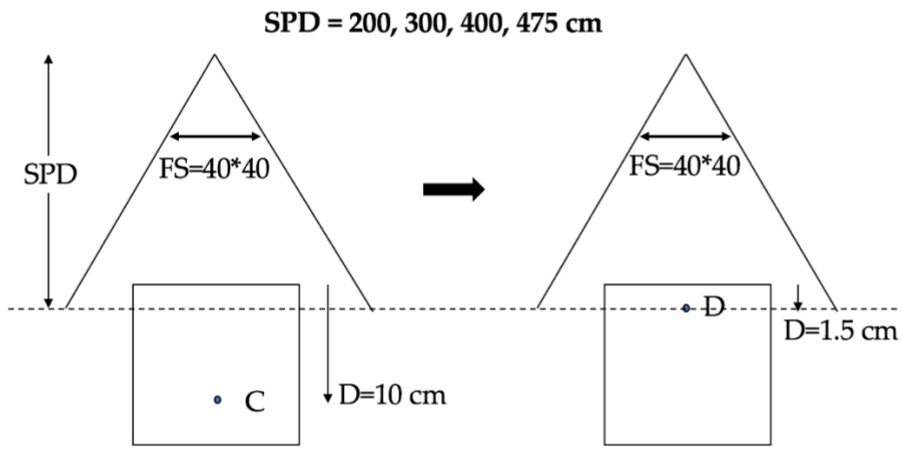

Figure 3: Output at SPD (200, 300, 400, or 475 cm). In Eclipse, the dose is calculated at point C, 10 cm depth, then converted to the dose at point D, 1.5 cm depth.

To verify that the output falls off with distance increasing following the inverse square law, the dose rates that obeys the inverse square law were calculated manually at different distances, then compared with the dose rates calculated by Eclipse as well.

$$D(d = 1.5cm, SPD, FS = 40 \times 40cm^2) = S_c(40 \times 40) \cdot S_p(30 \times 30) \cdot \left(\frac{101.5}{SPD}\right)^2$$

where S_c is the collimator scatter factor, collimator field size is 40×40 cm^2. S_p is the phantom scatter factor, the phantom size is 30×30 cm^2. Both S_c and S_p were acquired from the TBI Databook. $\left(\frac{101.5}{SPD}\right)^2$ is the component of inverse square. For the NovalisBlue Machine, $S_c(40 \times 40)$ is 1.057 and $S_p(30 \times 30)$ is 1.039. For the TBRed machine, $S_c(40 \times 40)$ is 1.047 and $\mathrm{S_p}(30 \times 30)$ is 1.057.

By comparing the results of output calculated by Eclipse and the output calculated following the inverse square, these two did not agree well for the TBRed machine. To explore the accuracy of outputs, a measurement was conducted to verify what the dose rate is in reality for the TBRed machine. The geometry setup is the same as the geometry in the Eclipse and commissioning.

3.2.2 Phantom Scatter Factor

The scatter factor can be separated to collimator scatter factor (S_c) and phantom scatter factor (S_p).[4] Because the collimator field size is always 40×40 cm^2 for total body irradiation, the collimator scatter factor is assumed to be constant in this case. Therefore, the verification of collimator scatter factor does not take into consideration. We only verified the phantom scatter factor, which is the ratio of the dose rate of a given phantom size at a certain depth to the dose rate of a reference phantom size at the same depth.[4] Phantom scatter factor is a scatter correction for the machine output due to the variation of patients' body size,[5] which is the patients equivalent square. The equivalent square converts the long rectangular field to the equivalent square that is more convenient for the commissioning test and dose calculation. In the Duke University Medical Center, the refence phantom size is 25×25 cm^2.

8 phantoms with different sizes were created in the Eclipse. The phantom size varies from 5×5 cm^2 to 40×40 cm^2 in 5 cm increments. The dose was calculated at 475 cm SPD for the NovalisBlue machine and 400 cm SPD for the TBRed machine with 40×40 cm^2 collimator field size and at 1.5 cm depth in the Eclipse (shown in figure 4). The dose rates were normalized to the dose rates at phantom size of 25×25 cm^2 for the comparison with the phantom scatter factors in TBI Databook.

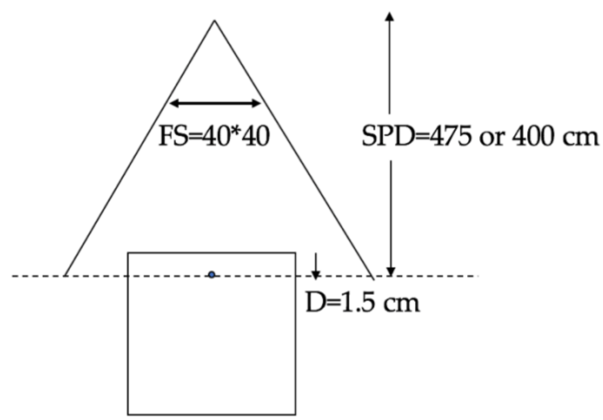

Figure 4: Phantom scatter factor. The phantom size varies from 5*5 to 40*40 cm. the dose is calculated at 1.5 cm depth and at 475 or 400 cm SPD.

3.2.3 Off-Axis Ratio

The off-axis ratio is the ratio of the dose rate at the point that located at off-axis distance x cm to the dose rate at the central axis.[4] Because the central axis is set up at the patient’s umbilicus level, patient’s head, lung, low legs are away from the beam central axis, off-axis dose correction is necessary when calculating the dose to these body parts. The off-axis dose correction depends on the depth and the distance away from the central axis.

In Eclipse, a long rectangular phantom, 30×30×180 cm^3, was created for the off-axis ratio verification. The geometry was set up to 40×40 collimator field size and 475 cm or 400 cm SPD at 5 cm depth (Figure 5). The dose is calculated at the central axis and the points off central axis distance in 9.5 cm increments for the NovalisBlue machine and in 8 cm increments for the TBRed machine, corresponding to 2 cm at 100 cm distance from the source.

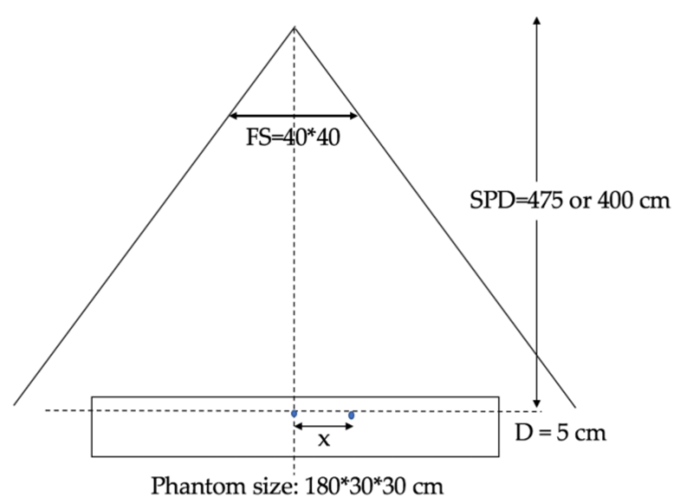

Figure 5: Off-axis ratio at 475 or 400 cm SPD. The dose is calculated at 5 cm depth. Off-axis distance is x, which is the distance that away from the central axis.

3.2.4 Tissue Maximum Ratio

Tissue Maximum Ratio (TMR) is a special case of Tissue phantom ratio (TPR), which is the ratio of dose rate at a certain depth to the dose rate at the same distance but at the d_{max}.[4] TMR is the important component in the dose calculation for the total body irradiation, which only depends on the field size and the depth and is independent on the distance.[4] Thus, the TMR is more practical than PDD in the TBI calculation.

In the TBI Databook, the phantom field sizes of TMR vary from 4×4 cm^2 to 40×40 cm^2, the depths for each field size vary from 1.5 cm to 31 cm, they are within the clinical range. In order to verify the TMR for the total body irradiation, 4 phantoms, sizes vary from 10×10×35 cm^3 to 40×40×35 cm^3 with 10 cm increments, were created in the Eclipse. Doses were calculated at 475 cm SPD (the NovalisBlue machine) or 400 cm SPD (the TBRed machine) and at 5 cm to 30 cm depth with the 40×40 cm^2 collimator field size (shown as figure 5). For the data comparison, both the TMR data in the TBI Databook and dose calculated by Eclipse were normalized to the dose at 5 cm depth for each phantom field size.

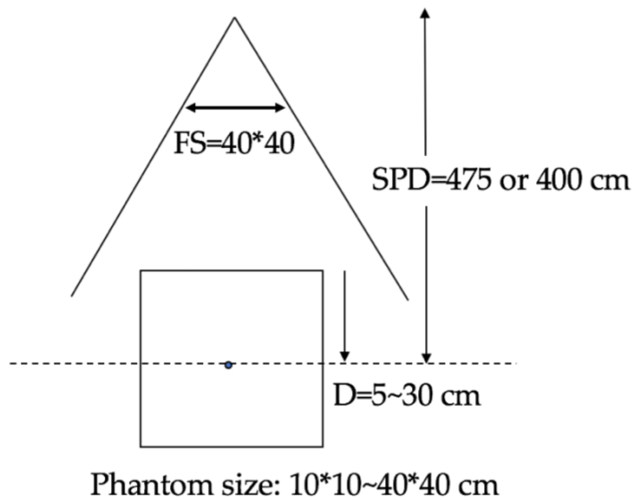

Figure 6: TMR. Phantom size varies from 10*10 to 40*40 cm. The depth varies from 5 to 30 cm. The dose is calculated at 475 or 400 cm SPD.

3.2.5 Spoiler Factor

There is skin sparing effect for the photon energy due to the electron fluence incident.[4] Extended treatment distance for total body irradiation increases the skin sparing. However, the skin sparing is not desirable in TBI because the surface dose is usually much lower than 90% of the maximum dose.[5] Therefore, a beam spoiler is placed during the treatment to increase the surface dose to at least 90% of the prescription dose for achieving dose uniformity.[5] Beam spoiler slightly decreases the dose beyond the buildup region at the same time. The spoiler factor is the ratio of the dose at a certain depth (5 cm or 10 cm) with spoiler to the dose at the same depth without spoiler. For different Linac, the spoiler factors are slightly different due to the difference of dosimetry data and treatment distance.

Generally, the closer the beam spoiler is placed to the patient, the higher surface dose is. At Duke University Medical Center, the spoiler is placed at the 1.5 meters away from the patient's midline. For the spoiler factor verification, a 30×30×160 cm^3 phantom was created in the Eclipse. In addition, a beam spoiler, which is 2 meters width, 1.5 meters height and 0.5 inches thickness was created besides the phantom. The spoiler is made of acrylic. The density was set to 1.18 cm^3/g, which is 265 HU in the Eclipse. Because of the limitation of the Eclipse, the largest image set is only 200×200 cm^2. The longest distance that beam spoiler to the phantom is about 80 cm in Eclipse instead of 150 cm in reality. Thus, two skin-to-spoiler distances (SkSpD), one is 20 cm and another is 65 cm, were set in the Eclipse to verify the spoiler factors at different SkSpD and compare the surface dose shift. When designing the plan for spoiler factor verification, two beam fields, one from right and one from left, were added and deliver the same MU to the phantom. One field had beam spoiler and another field was without spoiler (shown in figure 6). The geometry setup was the same as mentioned before, 40×40 collimator field size and 475 cm or 400 cm SPD. The doses were calculated at 10 cm depth for those two fields separately.

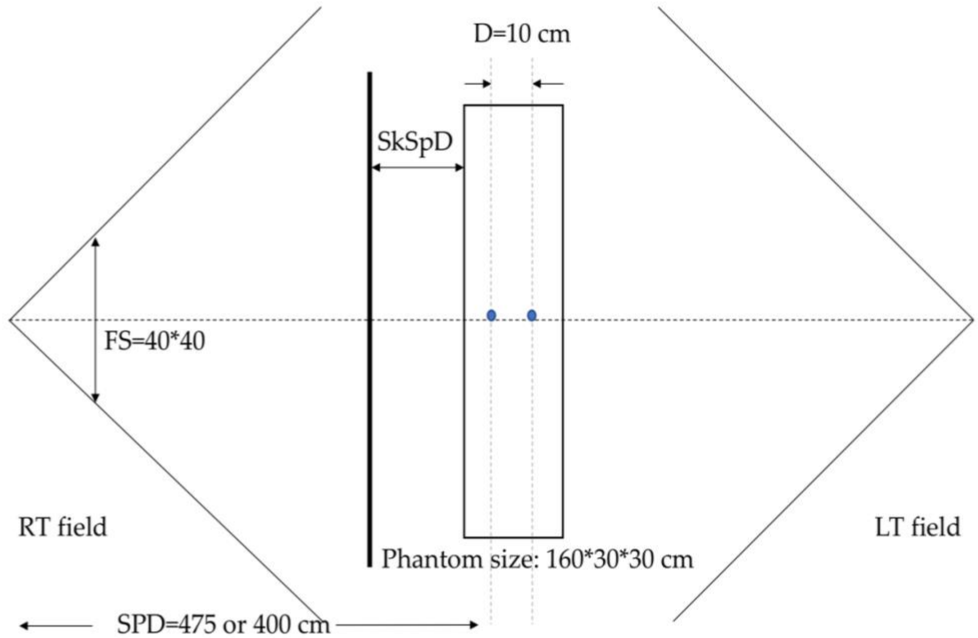

Figure 7: Spoiler is placed at the right side of the phantom. The doses are calculated at 10 cm depth from two fields, RT field is with spoiler and LT field is without spoiler.

3.2.6 Compensator Transmission Factor

Compensators are implemented for the dose uniformity due to the irregular surface shape, body separation variations and tissue density heterogeneities.[5] The compensators are made of brass in Duke University Medical Center. Each piece of brass is 1 mm. Those brass compensators can be taped up to make any desirable thickness. Compensator transmission factor is defined by the ratio of the dose rate at the certain depth with compensators to the dose rate at the same depth without compensators, the depth is 10 cm generally. Transmission factors for compensators with different thickness were measured in the clinical commissioning tests. In order to verify the transmission factors in Eclipse, the average transmission factor for one piece of brass is calculated manually via the equation below.

$$Transmission\ Factor = e^{-\mu d}$$

$$\ln(Transmission\ Factor) = -\mu d$$

where d is the thickness of brass, μ is the brass attenuation coefficient. By calculating the best-fit line of $\ln(Transmission\ Factor)$, attenuation coefficient μ was obtained. Then 4 blocks with different transmission factors were added in the Eclipse, which are

Block_1= $e^{-\mu*0.1}$

Block_2= $e^{-\mu*0.2}$

Block_5= $e^{-\mu*0.5}$

Block_10= $e^{-\mu*1.0}$

The subscript indicates the number of brass sheet that combine together to form a compensator. For example, block_2 means that two pieces of brass sheet are combined together. Any thickness of brass compensators can be assembled by those 4 blocks. For example, 19 pieces of brass compensators can be made by combining 1 Block_10, 1 Block_5, and 2 Bolock_2s in Eclipse.

The phantom used for verification of transmission factor in the Eclipse is 30×30×30 cm^3. The geometry was setup at 475 cm SPD with 40×40 cm^2 collimator field size. The compensators were added piece by piece, from 1 brass sheet to 25 brass sheets. The doses were calculated at 10 cm depth. The dose rates with compensators were then divided by the dose rate without compensators, which were the transmission factors for the compensators versus different thickness.

3.2.6 The Influence of Patient's Size to the Dose Distribution

Because the dose is prescribed at the point at the midline of patient's body, the surface dose and maximum dose is generally higher than the dose at midline in order to achieve the prescription dose insider the body. The patient's sizes have influence on the dose distribution. To investigate the surface dose and maximum dose of different patient's body size, we created 4 rectangular phantoms with various sizes approximating the normal patients' body sizes and compared their dose profiles at the umbilicus level.

4 rectangular phantoms, ranges from 20×20×160 cm^3 to 50×20×160 cm^3 in 10 cm increments, were created in the Eclipse. The MUs that delivered to these phantoms were calculated by the "TBI Calc" program, the calculation process of the program is illustrated in the chapter 2. The dose profiles of different phantom sizes were all normalized to the prescription dose.

3.3 Results

3.3.1 Output

The outputs calculation in Eclipse for the NovalisBlue machine and the TBRed machine are shown in Table 1 and Table 2. The outputs were calculated at the 10 cm depth and then converted to the output at 1.5 cm depth, which are in the first and second column. The percentage differences are the comparison of the output calculated by Eclipse with output calculated by following the inverse square law and the output in TBI Databook, respectively.

At the standard distance, 100 cm SSD, both the NovalisBlue machine and the TBRed machine show a great agreement with the TBI Databook, their differences are within 0.5%. At the SPD of 200 cm, 300 cm, 400 cm and 475 cm, the maximum difference between outputs by Eclipse and inverse square are 1.1% for the NovalisBlue machine. At the treatment distance of 475 cm SPD, the difference of the output and the TBI Databook is 1.4%. For the TBRed machine, the output calculated by Eclipse are lower than the output that following the inverse square, their differences are all more than 2% at difference SPD. However, the output in Eclipse at treatment distance is greater than the output in the TBI Databook.

The output measurements for the TBRed machine and the comparison with the outputs calculated by the Eclipse are shown in table 3. The measured outputs at the different distances have smaller difference in general, except for the output at 300 cm SPD.

Table 1: Outputs for the NovalisBlue machine at difference distances. The percentage differences are all compared with the output at 1.5 cm depth calculated by Eclipse.

Distance (cm)	Eclipse (d=10cm) (cGy/MU)	Eclipse (d=1.5cm) (cGy/MU)	Inverse Square (cGy/MU)	% diff	Databook (d=1cm) (cGy/MU)	% diff
Calibration SSD = 100	0.6659	0.9954	1.0000	-0.5%		
SPD = 200	0.215	0.2805	0.2829	-0.8%		
SPD = 300	0.0979	0.1243	0.1257	-1.1%		
SPD = 400	0.0562	0.0704	0.0707	-0.5%		
SPD = 475	0.0406	0.0505	0.0501	0.7%	0.0498	1.4%

Table 2: Outputs for the TBRed machine at difference distance. The percentage differences are all compared with the output at 1.5 cm depth calculated by Eclipse.

Distance (cm)	Eclipse (d=10cm) (cGy/MU)	Eclipse (d=1.5cm) (cGy/MU)	Inverse Square (cGy/MU)	% diff	Databook (d=1cm) (cGy/MU)	% diff
Calibration SSD = 100	0.6645	1.0008	1.0000	0.1%		
SPD = 200	0.2120	0.2776	0.2850	-2.6%		
SPD = 300	0.0967	0.1232	0.1267	-2.7%		
SPD = 400	0.0555	0.0697	0.0713	-2.1%	0.0682	2.2%

Table 3: Outputs for the TBRed machine at difference distances. The percentage differences are all compared with the outputs calculated by Eclipse.

Distance (cm)	Eclipse (d=10cm) (cGy/MU)	Eclipse (d=1.5cm) (cGy/MU)	Inverse Square (cGy/MU)	% diff	Measure (d=1.5cm) (cGy/MU)	% diff
Calibration SSD = 100	0.6645	1.0008	1.0000	0.1%	1	0.08%
SPD = 200	0.2120	0.2776	0.2850	-2.6%	0.2778	0.07%
SPD = 300	0.0967	0.1232	0.1267	-2.7%	0.1263	-2.6%
SPD = 400	0.0555	0.0697	0.0713	-2.1%	0.0698	0.1%

3.3.2 Scatter Factor

Table 4 and Table 5 show the phantom scatter factors that normalized to the phantom scatter at 25×25 cm field size versus the phantom sizes and their differences with the TBI Databook for the NorvalisBlue machine and the TBRed machine, respectively. The phantom scatter factors calculated by Eclipse agree well with TBI Databook for large fields (larger than 15×15 cm). For the 5×5 cm and 10×10 cm field sizes, the phantom scatter factors calculated by Eclipse are greater than that in TBI Databook. Figure 8 and Figure 9 show their trends with the phantom sizes.

Table 4: Phantom scatter factors versus the field sizes for the NorvalisBlue machine. The differences are between the phantom scatter factor in TBI Databook and Eclipse.

Phantom size(cm)	Databook	Eclipse	% diff
5	0.951	0.976	2.66%
10	0.968	0.980	1.26%
15	0.984	0.988	0.42%
20	0.993	0.996	0.31%
25	1.000	1.000	0%
30	1.006	1.008	0.19%
35	1.012	1.012	0%
40	1.016	1.016	0%

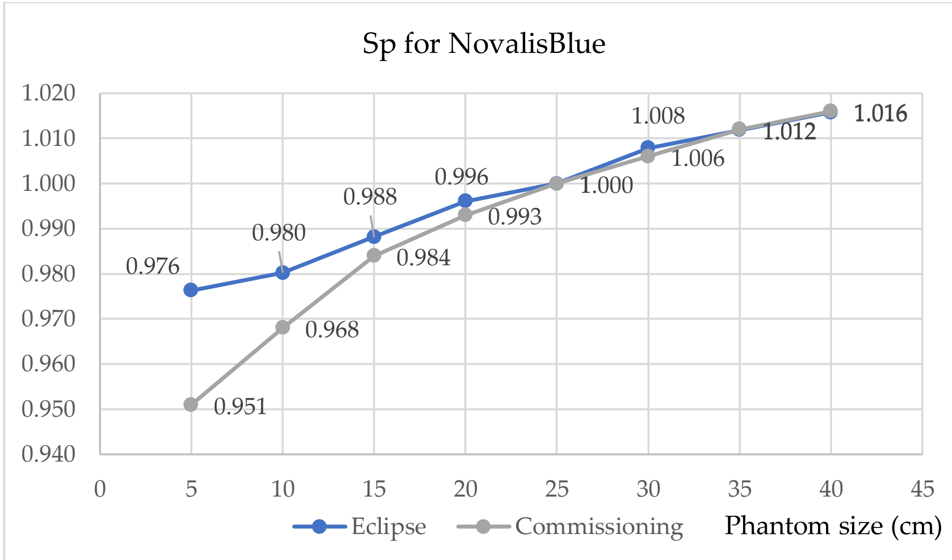

Figure 8: Phantom scatter factors in Eclipse and TBI Databook versus the field sizes for the NorvalisBlue machine.

Table 5: Phantom scatter factors versus the field sizes for the TBRed machine. The differences are between the phantom scatter factor in TBI Databook and Eclipse.

Phantom size(cm)	Databook	Eclipse	% diff
5	0.922	0.974	5.67%
10	0.956	0.974	1.91%
15	0.977	0.986	0.89%
20	0.990	0.994	0.43%
25	1.000	1.000	0.00%
30	1.011	1.006	-0.52%
35	1.014	1.009	-0.54%
40	1.024	1.011	-1.23%

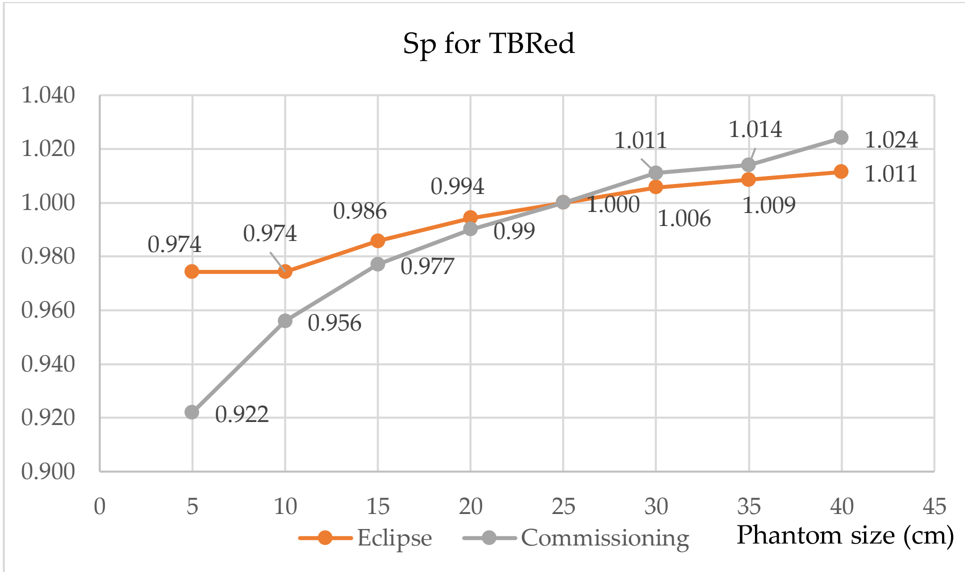

Figure 9: Phantom scatter factors in Eclipse and TBI Databook versus the field sizes for the TBRed machine.

3.3.3 Off-axis Ratio

Off-axis ratios for the NovalisBlue machine and the TBRed machine with the off-axis distances are shown in Table 6 and Table 7. All off-axis ratios are normalized to the off-axis ratio at the central axis, which is at 0 cm off-axis distance. Off-axis ratios calculated in Eclipse have a great agreement with that in TBI Databook, the percentage differences are all within 0.5% for both the NovalisBlue machine and the TBRed machine.

Table 6: Off-axis ratios at difference off-axis distance in Eclipse and they were compared with the OARs in TBI Databook for the NovalisBlue machine.

Off-axis distance (cm) at 100 SAD	Off-axis distance (cm) at 475 SPD	Databook OAR at 5 cm depth	Eclipse OAR at 5 cm depth	% diff
0	0	1	1	0.00%
2	9.5	1.010	1.012	0.24%
4	19	1.022	1.023	0.08%
6	28.5	1.032	1.033	0.12%
8	38	1.036	1.039	0.33%
10	47.5	1.038	1.041	0.34%
12	57	1.043	1.046	0.25%
14	66.5	1.044	1.046	0.16%
16	76	1.044	1.046	0.16%

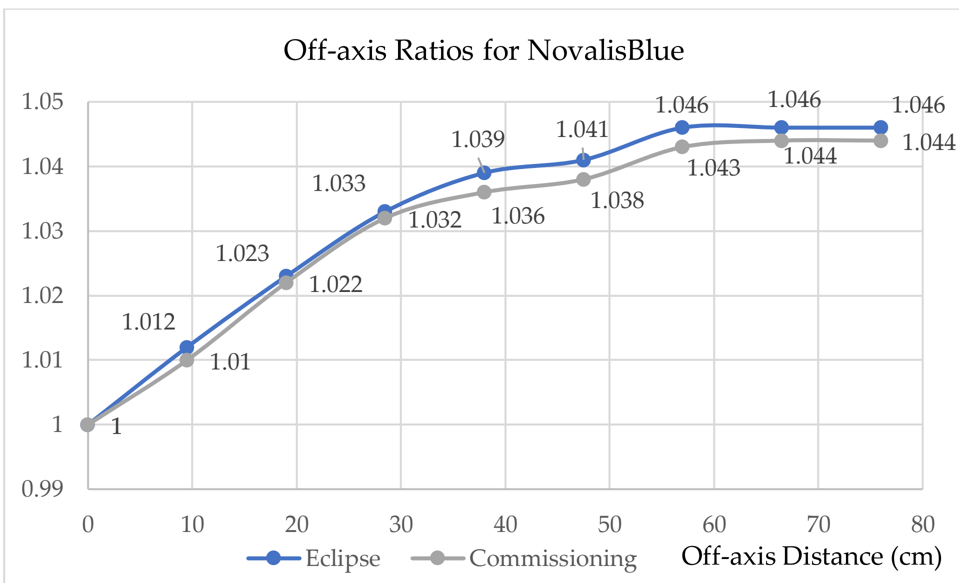

Figure 10: Off-axis ratios versus the off-axis distance at 475 cm SPD and 5 cm depth for the NovalisBlue machine.

Table 7: Off-axis ratios at difference off-axis distances in Eclipse and they were compared with OARs in TBI Databook for the TBRed machine.

Off-axis distance (cm) at 100 SAD	Off-axis distance (cm) at 475 SPD	Databook OAR at 5 cm depth	Eclipse OAR at 5 cm depth	% diff
0	0	1	1	0
2	8	1.010	1.006	-0.40%
4	16	1.022	1.018	-0.39%
6	24	1.032	1.027	-0.48%
8	32	1.036	1.033	-0.29%
10	40	1.038	1.039	0.10%
12	48	1.043	1.042	-0.09%
14	56	1.044	1.042	-0.19%
16	64	1.044	1.045	0.10%

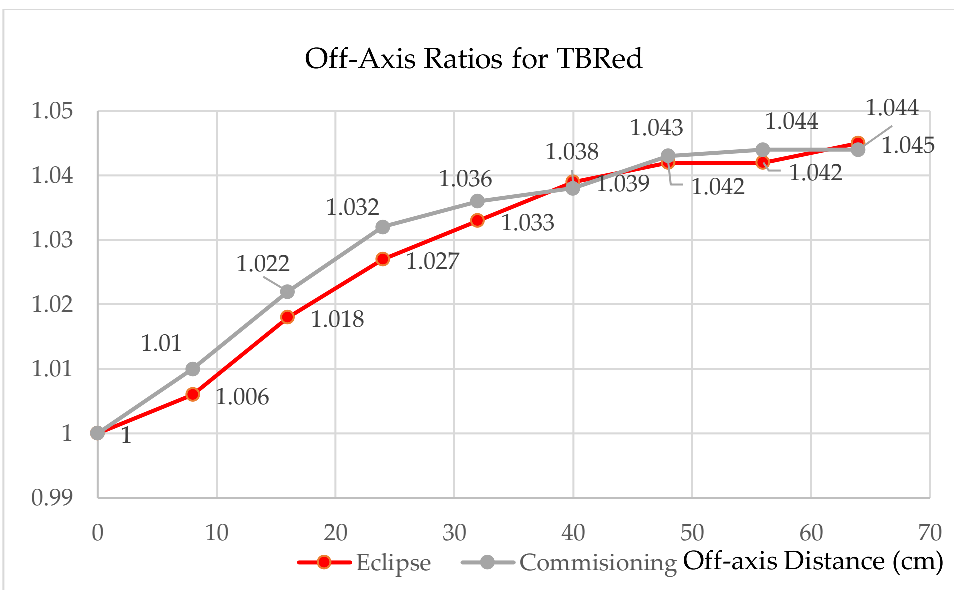

Figure 11: Off-axis ratios versus the off-axis distance at 400 cm SPD and 5 cm depth for the TBRed machine.

3.3.4 Tissue Maximum Ratio

TMRs at different depths are all normalized to the TMR at 5 cm depth for the given field sizes, which are shown in Table 7 and Table 8 for the NovalisBlue and the TBRed machine, respectively. For the NovalisBlue machine, the maximum difference between the TMRs calculated in Eclipse and in the TBI Databook is 1.6% in 20×20 cm field size at 30 cm depth and most of the percentage differences are below 1%. For TBRed machine, the maximum difference is 1.95% in 10×10 cm field size at 25 cm depth and most of the percentage differences are below 1% as well. The less differences are in the large field size generally.

Table 8: Normalized TMRs in TBI Databook and Eclipse for the NovalisBlue machine. The differences are the comparison between those two.

Phantom field size (cm)	Depth (cm)	TMR from Databook	Normalized TMR from Databook	Normalized TMR from Eclipse	% diff
10	5	0.922	1	1	0.00%
	10	0.776	0.842	0.841	-0.11%
	15	0.636	0.690	0.690	0.00%
	20	0.515	0.559	0.562	0.60%
	25	0.415	0.450	0.456	1.25%
	30	0.334	0.362	0.367	1.38%
20	5	0.936	1	1	0.00%
	10	0.812	0.868	0.868	0.00%
	15	0.687	0.734	0.735	0.15%
	20	0.574	0.613	0.611	-0.35%
	25	0.472	0.504	0.509	0.85%
	30	0.386	0.412	0.419	1.60%
30	5	0.942	1	1	0.00%
	10	0.833	0.884	0.874	-1.17%
	15	0.717	0.761	0.756	-0.64%
	20	0.607	0.644	0.643	-0.24%

	25	0.508	0.539	0.538	-0.27%
	30	0.420	0.446	0.445	-0.11%
40	5	0.949	1	1	0.00%
	10	0.844	0.889	0.884	-0.62%
	15	0.732	0.771	0.772	0.06%
	20	0.626	0.660	0.660	0.00%
	25	0.530	0.558	0.556	-0.44%
	30	0.443	0.467	0.469	0.44%

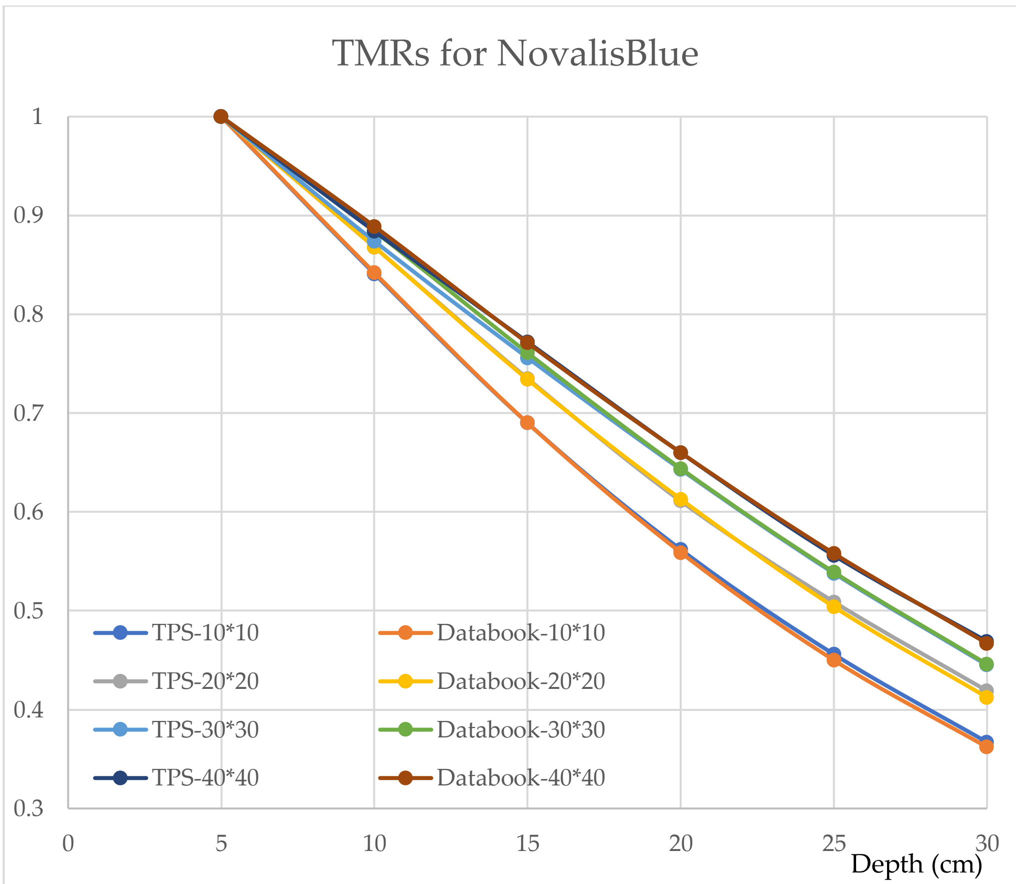

Figure 12: Normalized TMR for the NovalisBlue machine with different phantom sizes versus depth. The results are normalized to the TMR at 5 cm depth for each field size.

Table 9: Normalized TMRs in the Databook and Eclipse for the TBRed machine. The differences are the comparison between those two.

Phantom field size (cm)	Depth (cm)	TMR from Databook	Normalized TMR from Databook	Normalized TMR from Eclipse	% diff
10	5	0.929	1	1	0
	10	0.774	0.833	0.842	1.12%
	15	0.637	0.686	0.695	1.29%
	20	0.518	0.558	0.566	1.49%
	25	0.419	0.451	0.460	1.95%
	30	0.341	0.367	0.373	1.62%
20	5	0.934	1	1	0.00%
	10	0.812	0.869	0.870	0.07%
	15	0.689	0.738	0.740	0.31%
	20	0.575	0.616	0.619	0.58%
	25	0.477	0.511	0.514	0.63%
	30	0.394	0.422	0.424	0.55%
30	5	0.94	1	1	0.00%
	10	0.83	0.883	0.881	-0.17%
	15	0.717	0.763	0.763	0.02%
	20	0.61	0.649	0.647	-0.23%
	25	0.514	0.547	0.544	-0.50%
	30	0.429	0.456	0.456	-0.10%
40	5	0.943	1	1	0.00%
	10	0.84	0.891	0.886	-0.51%
	15	0.732	0.776	0.769	-0.87%
	20	0.628	0.666	0.659	-1.09%
	25	0.535	0.567	0.563	-0.79%
	30	0.451	0.478	0.473	-1.09%

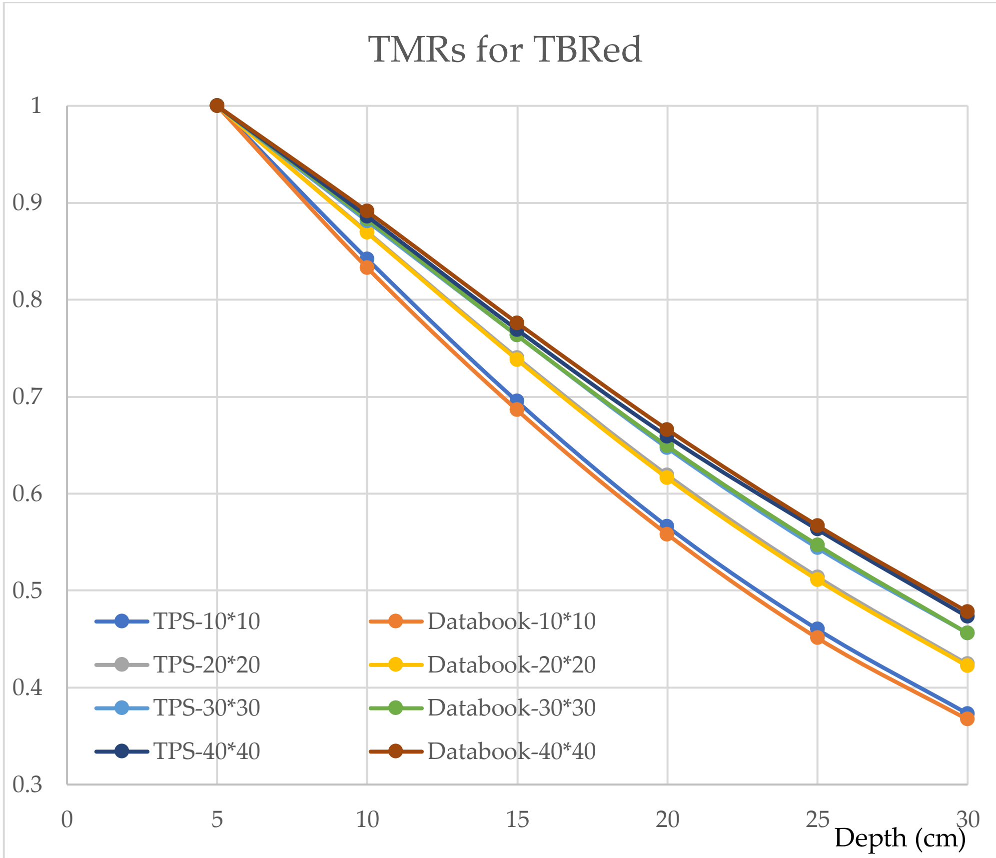

Figure 13: Normalized TMR for the TBRed machine with different phantom sizes versus depth. The results are all normalized to the TMR at 5 cm depth for each field size.

3.3.5 Spoiler Factor

The spoiler factors at skin-to-spoiler distance of 65 cm and 20 cm for the NovalisBlue and the TBRed machine are shown in Table 10. Figure 14 to Figure 17 demonstrate the dose profiles at the central axis of the phantom from the surface to the 30 cm depth with spoiler and without spoiler for those two machines at two skin-to-spoiler distances, respectively. The percentage differences are all below 1%.

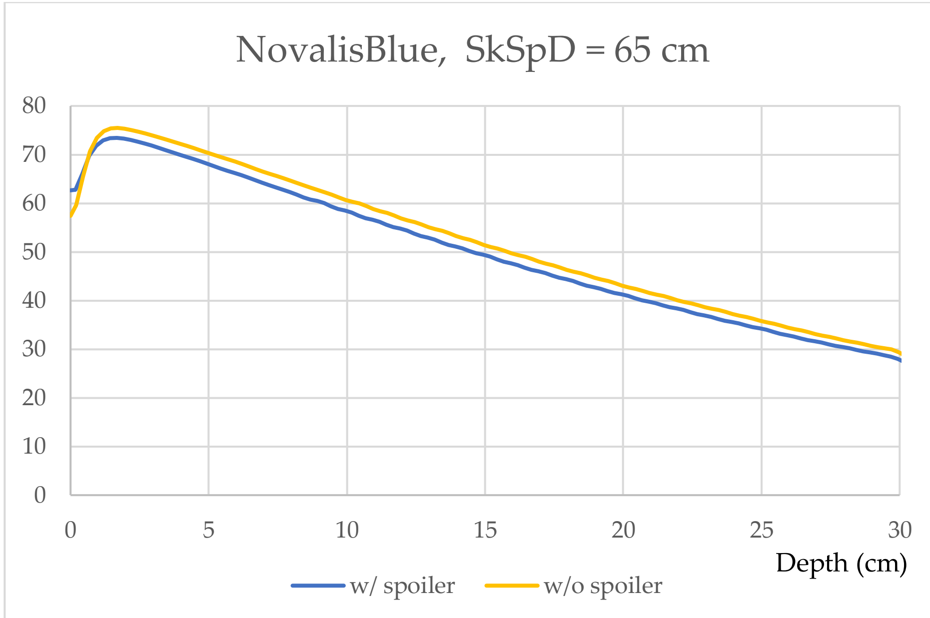

Figure 14: Dose profiles with and without spoiler at 65 cm skin to spoiler distance for the NovalisBlue machine.

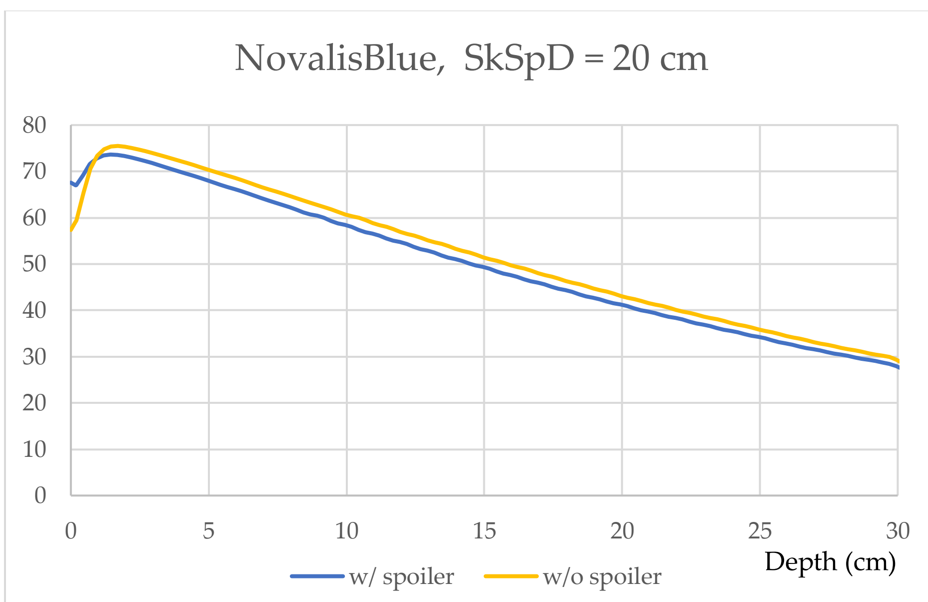

Figure 15: Dose profiles with and without spoiler at 20 cm skin to spoiler distance for the NovalisBlue machine.

Figure 16: Dose profiles with and without spoiler at 65 cm skin to spoiler distance for the TBRed machine.

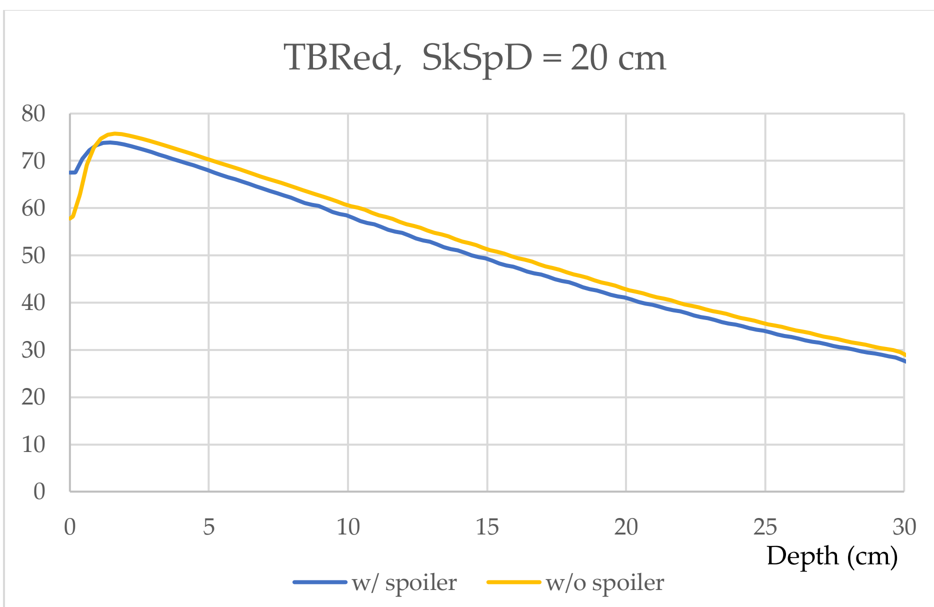

Figure 17: Dose profiles with and without spoiler at 20 cm skin to spoiler distance for the TBRed machine.

Table 10: Spoiler factors in TBI Databook and calculated in Eclipse at difference skin to spoiler distances and their differences for the NovalisBlue and TBRed machine.

Machine	Spoiler factor in Databook	SkSp distance (cm)	Spoiler factor from Eclipse	% diff
NovalisBlue	0.956	65	0.964	0.8%
		20	0.963	0.7%
TBRed	0.954	65	0.964	1.0%
		20	0.963	0.9%

3.3.6 Compensator Transmission Factor

Figure 18 shows that the slope of $\ln(Transmission\ Factor)$ is -0.0303, which means brass attenuation coefficient μ for brass is 0.0303.

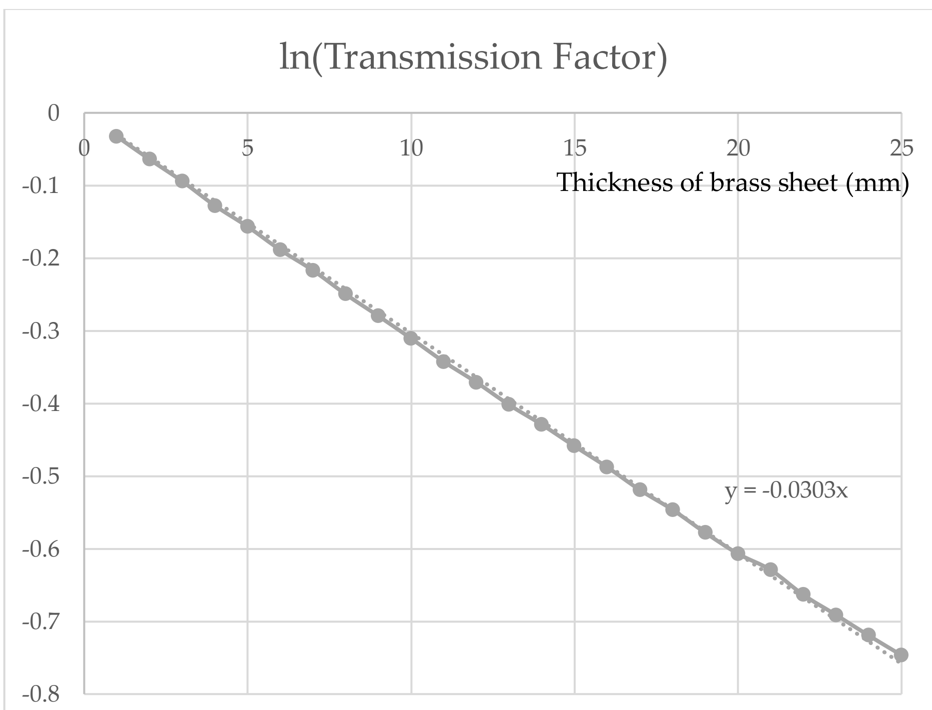

Figure 18: ln(transmission factor) versus the pieces number of brass compensators. The slope of best fit line is 0.0303.

Thus, the transmission of blocks that added into the Eclipse are list below.

$$\text{Block\_1} = e^{-0.0303*0.1} = 0.97015$$

$$\text{Block\_2} = e^{-0.0303*0.2} = 0.94120$$

$$\text{Block\_5} = e^{-0.0303*0.5} = 0.85942$$

$$\text{Block\_10} = e^{-0.0303*1.0} = 0.73860$$

The compensator transmission factors were verified piece by piece. Their combination method and the transmission factors calculated by Eclipse are shown in Table 11 and Figure 19. Most transmission factors agree well with the TBI Databook, their percentage differences are all below 1.1%.

Table 11: Transmission factors verified in Eclipse and the percentage differences with the TBI Databook.

Number of brass sheets	Transmission factor in Databook	Compensator combinations in Eclipse	Transmmision factor from Eclipse	% diff
1	0.968	1 brass_1	0.970	0.3%
2	0.938	1 brass_2	0.941	0.4%
3	0.91	1 brass_1 1 brass_2	0.914	0.4%
4	0.880	2 brass_2	0.887	0.7%
5	0.855	1 brass_5	0.860	0.6%
6	0.828	1 brass_1 1 brass_5	0.835	0.8%
7	0.805	1 brass_2 1 brass_5	0.810	0.6%
8	0.779	1 brass_1 1 brass_2 1 brass_5	0.786	0.9%
9	0.756	1 brass_5 2 brass_2	0.763	0.9%
10	0.733	1 brass_10	0.740	1.0%

11	0.710	1 brass_1 1 brass_10	0.718	1.1%
12	0.690	1 brass_10 1 brass_2	0.697	1.0%
13	0.669	1 brass_1 1 brass_2 1 brass_10	0.676	1.1%
14	0.651	2 brass_2 1 brass_10	0.656	0.8%
15	0.632	1 brass_5 1 brass_10	0.637	0.7%
16	0.614	1 brass_1 1 brass_5 1 brass_10	0.618	0.6%
17	0.595	1 brass_2 1 brass_5 1 brass_10	0.600	0.8%
18	0.579	1 brass_1 1 brass_2 1 brass_5 1 brass_10	0.582	0.5%
19	0.561	2 brass_2 1 brass_5 1 brass_10	0.564	0.6%
20	0.545	2 brass_10	0.548	0.6%
21	0.533	1 brass_1 2 brass_10	0.532	-0.3%
22	0.515	1 brass_2 2 brass_10	0.516	0.2%
23	0.501	1 brass_1 1 brass_2 2 brass_10	0.501	-0.1%
24	0.487	2 brass_2 2 brass_10	0.486	-0.2%
25	0.474	1 brass_5 2 brass_10	0.472	-0.5%

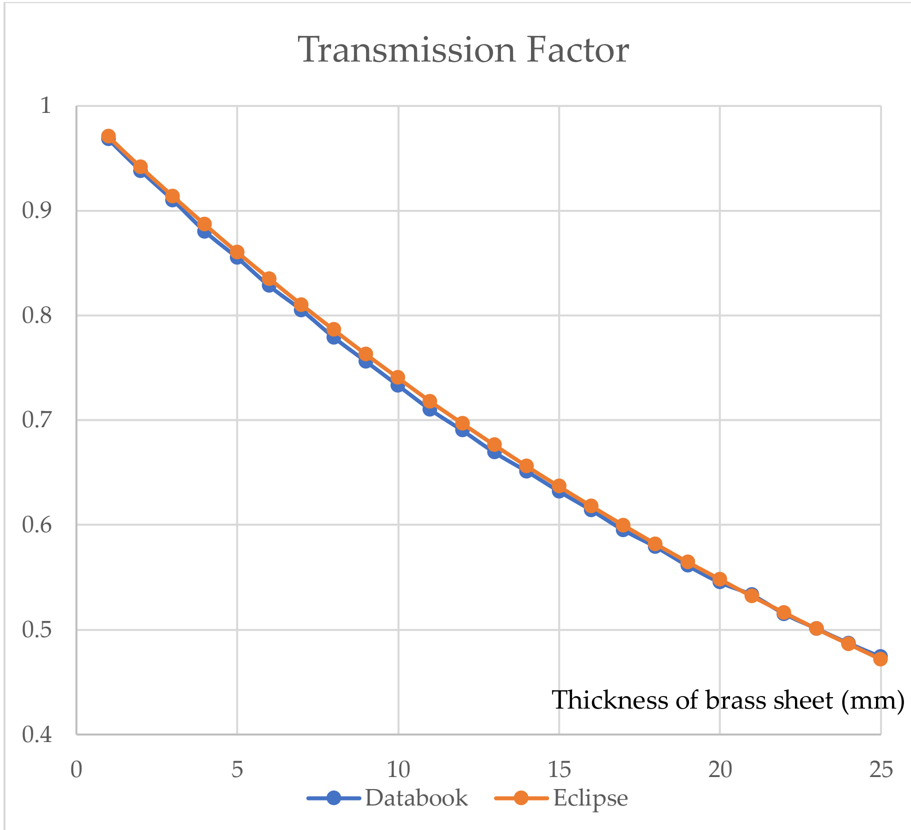

Figure 19: Transmission factors that calculated in Eclipse are compared with the TBI Databook.

3.3.7 The Influence of Patient's Size to Dose Distribution

The dose profile along 3 axes with different phantom size for the NovalisBlue and the TBRed machine were shown in Figure 20 to Figure 25 below. The dose profiles are all normalized to the prescription dose as 100%, which is shown as the relative dose in figure 20 and Figure 21, 0 in x-axis indicates the mid-depth of the phantom. y-axis is the percentage depth dose that is relative to prescription dose. The surface doses increase with the phantom sizes in order to deliver the prescribed dose to the mid-depth. For the phantom thickness of 50 cm, the surface relative dose achieves 125%, which is beyond the uniformity within 10%. The mid-depth doses for all phantom sizes are all around 100% of prescribed dose.

Figure 22 and Figure 23 describe the dose profile along the midline of the phantom. The relative doses are almost within 10%, however, the relative dose near the edge are less than 90%, it is more obvious for thicker phantom. Anteroposterior (AP) dose profiles along the phantom central axis are shown in Figure 24 and Figure 25. The relative dose at the edges are slightly higher than the dose at the center for the NovalisBlue machine. In contrast, the doses at the edges are lower than the dose at the center for the TBRed machine.

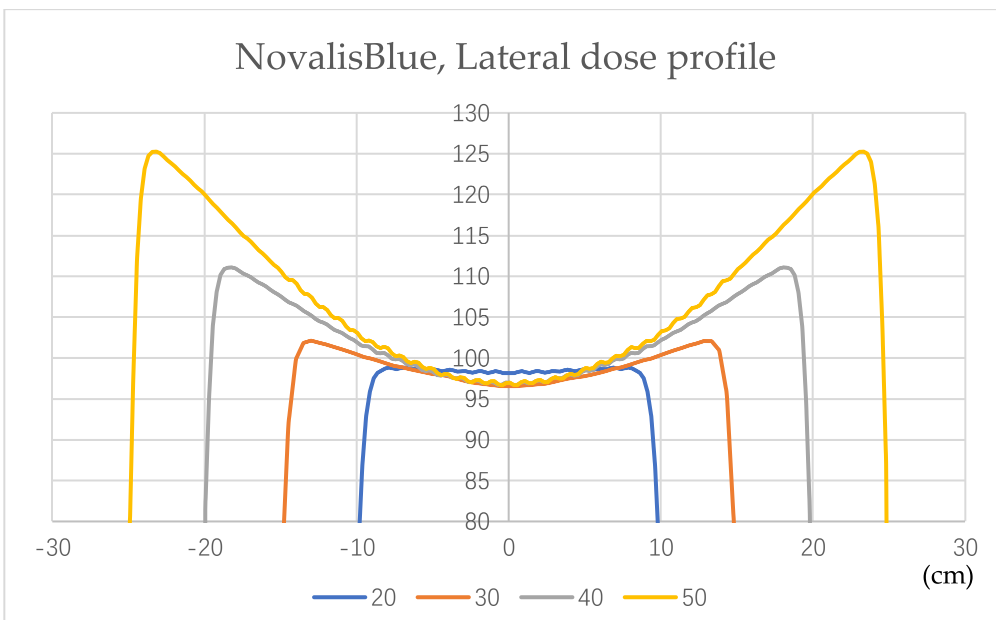

Figure 20: For the NovalisBlue machine, relative lateral dose profiles versus phantom size.

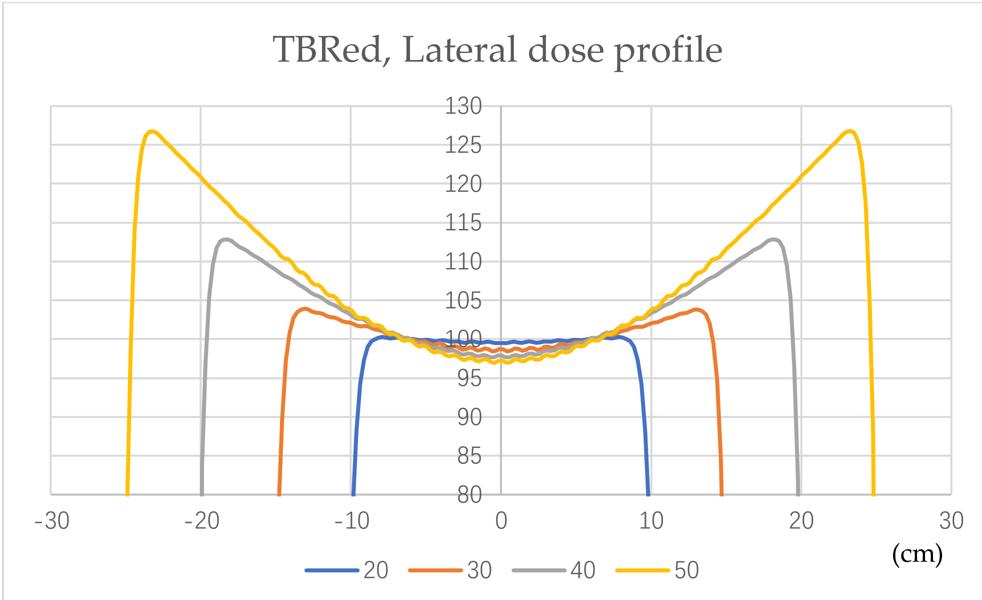

Figure 21: For the TBRed machine, relative dose profiles versus phantom size.

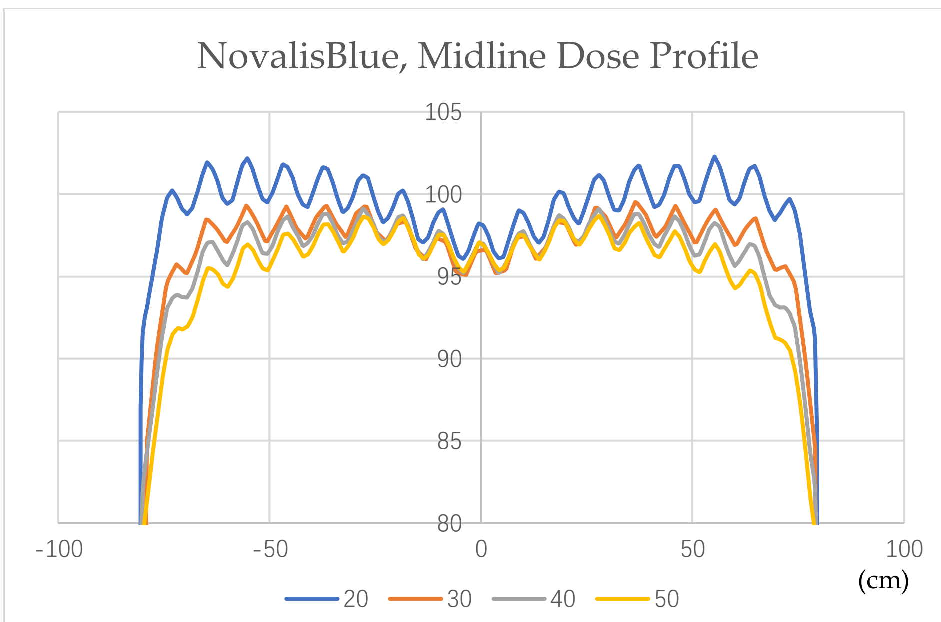

Figure 22: The relative dose profiles along superior-inferior direction with various phantom thicknesses for the NovalisBlue machine.

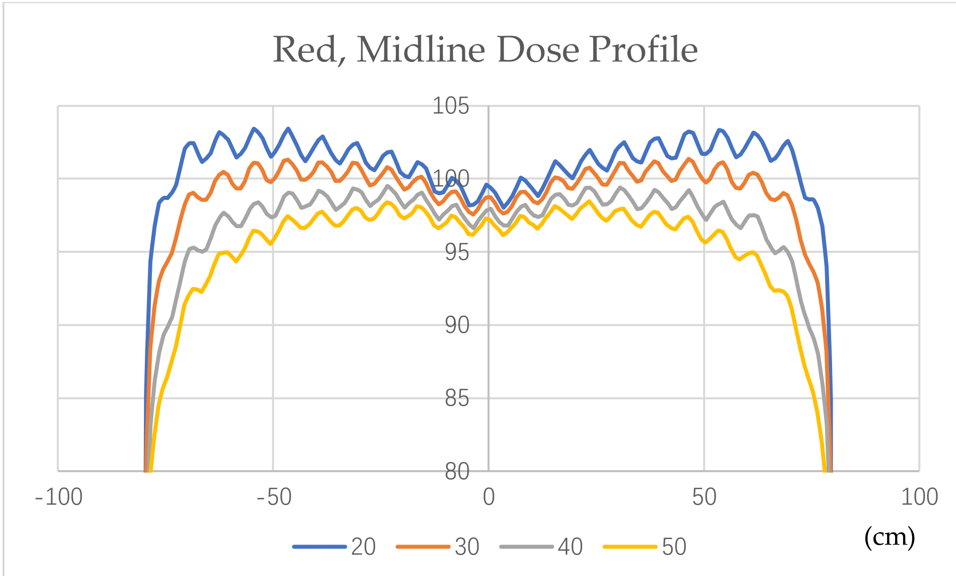

Figure 23: The relative dose profiles along superior-inferior direction with various phantom thicknesses for the TBRed machine

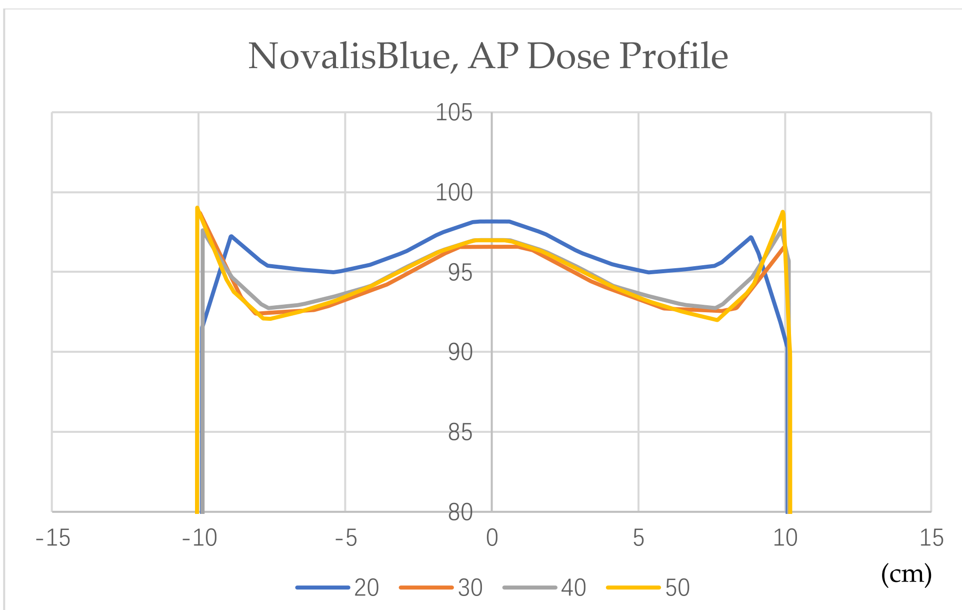

Figure 24: The relative AP dose profiles along the phantom central axis with various phantom thicknesses for the NovalisBlue machine

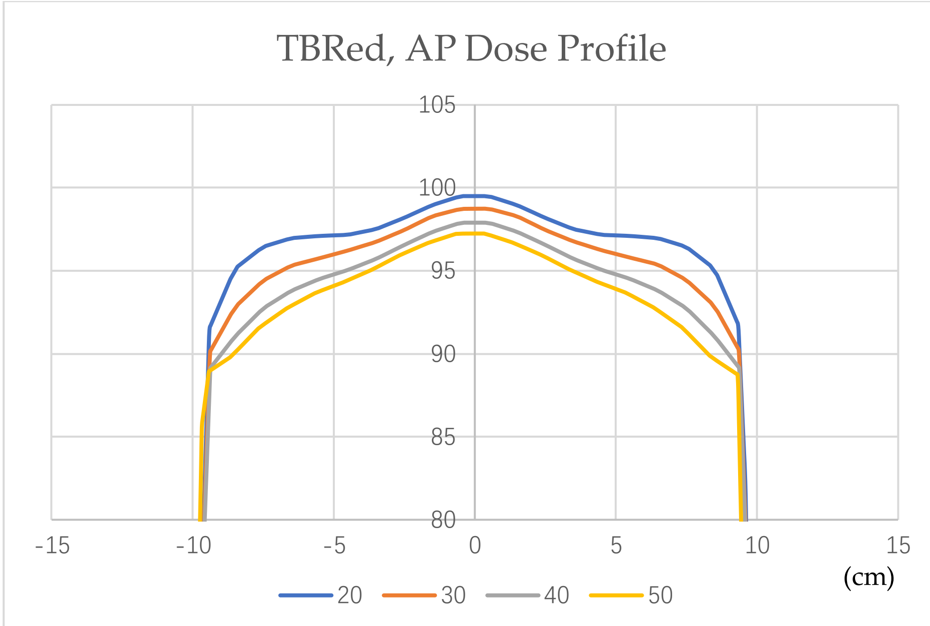

Figure 25: The relative AP dose profiles along the phantom central axis with various phantom thicknesses for the TBRed machine

3.4 Discussion

The results of Eclipse showed that output falls off with increasing distance; this follows the inverse square law. The measurements of output, however, do not exactly follow the inverse square law. Scatter is not only from phantom scatter and collimator scatter – which are considered in the calculation of the output for the inverse square law – but also from the floor and wall.[11] The outputs calculated by Eclipse for the NovalisBlue machine agree better with the inverse square law than that for the TBRed machine. At the treatment distance, output from Eclipse have better agreement with output from the TBI Databook for the NovalisBlue machine. Additionally, for the TBRed machine, outputs calculated at the various distances are always lower than the output based on inverse square by about 2%. In order to investigate the reasons, a measurement was conducted to determine the output at those distances for the TBRed machine.

The dose is measured at the 1.5 cm depth, the geometry is the same as how output calculated in the Eclipse. The results show that the measured outputs have better agreement with the output calculated by the Eclipse. However, in the TBI annual QA, we have found that when locating the d_{max} at treatment SPD, the setup is with spoiler and tray. Thus, the d_{max} is located at 1 cm depth. But when doing the output measurement, the spoiler and tray were taken out, the dose is measured at 1 cm depth still. Without spoiler and tray, 1 cm depth is at the build-up region, which means the dose at 1 cm depth is lower than dose at d_{max}. That illustrates the reason that why output calculated in the Eclipse at 1.5 cm depth is higher than output in the Databook for both the NovalisBlue and the TBRed machine.

Phantom scatter factors in small fields, such as 5×5 cm^2 and 10×10 cm^2 phantom size, show a worse agreement with TBI Databook. But it does not have much influence in the calculation for the TBI. Usually, the clinic range of the patient's equivalent square are larger than 20×20 cm^2, even for the pediatric patients. Hence, the phantom scatter factors calculated by Eclipse were acceptable when comparing to TBI Databook in clinic range.

The values of spoiler factors calculated in Eclipse at 20 cm skin-to-spoiler distance are closer to that in the TBI Databook than those at skin-to-spoiler distance of 65 cm. Moreover, the surface dose increases more at 20 cm distance than 65 cm, which is consistent with what we expect. The closer spoiler to the patient, the higher surface dose is.[5] However, in the actual measurement, surface dose that spoiler is placed at 35 cm skin-to-spoiler distance can achieve about 100% of the maximum dose. And surface dose is about 94% of the maximum dose at the 135 cm skin-to-spoiler distance. Therefore, the spoiler placed at 150 cm away from the patient's midline in actual treatment is enough for the dose uniformity.

In the dose profiles of these phantoms, there are some ripples along the midline. It may be caused by the calculation problems in Eclipse because Eclipse is not designed for this special dose calculation. The fluctuation of these ripples is less than 3%, which does not result in much influences when considering the overall dose profiles trends.

Off-axis ratios, tissue maximum ratios, and compensator transmission factors calculate by Eclipse match well with those values in the TBI Databook. Considering all the factors, the dosimetric data were validated comprehensively. The commissioning tests in Eclipse show promising results, which proves that Varian Eclipse can calculate the dose for TBI at the extended distance and for large field.

4. Total Body Irradiation Using Treatment Planning System

4.1 Introduction

Recently, some researches have investigated the use of Computed Tomography (CT)-based treatment planning for the total body irradiation.[11,19,20,21] It demonstrates that these treatment planning system can calculate dose distribution for total body irradiation. However, the treatment procedures are not described thoroughly. The treatment techniques and patients positioning can be diverse among different hospitals. This work is aim at verifying the feasibility of using treatment planning system to calculate total body irradiation treatment procedure at Duke University Medical Center.

The “TBI Calc” program at Duke University Medical Center is specifically designed for total body irradiation calculation, which is based on simple point dose calculation. The calculation results of the program are consistent with the hand calculation that illustrates in Chapter 2. The program has been applied for many years and the calculation results have been confirmed to be accurate. The doses measured by Optically Stimulated Luminescent Dosimeters (OSLDs) during the treatment are compared with the prescribed dose after the first treatment. The comparison results show that the calculation result by the program is reliable. But still, there are some limitations of this program. The OSLDs only measure the 2 points doses on the patient’s body surface during the treatment. The dose distribution of the whole body is obscure by the “TBI Calc” program and *in vivo* dose measurement.

In order to verify if Eclipse can be applied for TBI planning, the doses calculated by Eclipse are compared with the OSLD dose measurements and the prescribed dose. Patient' whole body CT is required in Eclipse for the dose calculation. However, total body irradiation patients generally do not undergo whole-body CT scans for two reasons: 1) he current calculation program does not require patient's whole-body CT, and; 2) the whole-body CT would add unnecessary dose to the patients. In the hand calculation or "TBI Calc" program, the tissue inhomogeneity is negligent. Patient's body is regarded as a homogeneous rectangular phantom and calculated using the equivalent square. Thus, a water equivalent phantom approximating patient's body shape can substitute the whole-body CT. For the purpose of verifying the accuracy of existing program, the patient's body shape phantom was regards as a combination of the several rectangular phantoms in the Eclipse, using the measured patient's dimensions data.

4.2 Methods

4.2.1 Phantom with the Patient's Body Shape

A rectangular phantom with 200 slices, 1 cm thickness for each slice, was created in the Eclipse, which means that the tallest patient we can create a phantom for them is 200 cm. Two structures, body and lung, were set in the rectangular phantom. For the lung, the HU value was set to -454, corresponding to the density 0.53 g/cm^3. Due to the clinic experience for many years, lung density was adjusted to 0.53 g/cm^3 in "TBI Calc" instead of 0.25 g/cm^3, which is the average lung density. In order to verify the accuracy of this program, the lung density in Eclipse is set to the same value as “TBI Calc”. The HU of the rest of body is 0 because it is regards as water equivalent.

The phantom was exported from the Eclipse and saved as DICOM files that consists of the RT structure information. Then the RT structure DICOM file was import into the MATLAB. An Excel file, which contains the patient’s measured data, was imported into MATLAB at the same time. The contouring points of these two structures in each slice were modified based on the patient’s dimensions and lung measurement data. Due to limited measured data, the dimensions of each slice in the phantom was interpolated between two measured areas. After modifying, the RT structure DICOM file was imported back into Eclipse. A phantom with lung structure approximating the individual patient’s body shape was prepared for the further treatment planning. Particularly, for the patient without lung dose limit, chest x-ray for lung dimensions measurement is unnecessary for the lung dose calculation. Because the patient phantom is created based on the measured body dimensions data, there is no lung structure created in the phantom for those patients without lung limit.

4.2.2 Treatment Planning System Using Eclipse

For each patient, the treatment plans were created by the “TBI Calc” program. There were two MUs calculated in the treatment plan. One is uncorrected MU, which neglects the correction for patient’s body sizes. Another is corrected MU, which takes patients size into consideration and increases or decrease the MU to enhance dose uniformity to the patient's whole body. In addition, the numbers of compensators for different body areas were calculated.

In the Eclipse, the same pieces of compensators were added as blocks for thinner body parts in the Eclipse. Because the phantom only had two structures, body and lung, the blocks can be only added using "freehand" function in Eclipse at the beam eye view when placing the compensators for the head, neck and low legs. For the lung compensators, the blocks can be added by choosing "fit to structure" function.

In the actual treatment, the gantry angle is tilted about 270 degrees. Patients' direction changes during the treatment to make the beam fields come from the patients' right side and left side respectively. However, in the Eclipse, patients' position is immobile. Two beam fields, one with 270 degrees gantry angle and another with 90 degrees gantry angle, were added for the phantoms instead. For each beam field, the collimator field size was set to 40×40 cm^2. Source to the surface distance (SSD) was set based on the patient's thickness to make sure the source to the patient midline distance (SPD) is 475 cm for the NovalisBlue machine and 400 cm for the TBRed machine.

In general, patients are treated using the corrected MUs to ensure the dose as uniform as possible. Thus, corrected MUs were entered for the dose calculation to compare with the *in vivo* measured doses. On the other hand, the uncorrected MU is calculated based on the hand calculation, it gives the prescribed dose to the center of the body parts in principle. Uncorrected MUs were used for the verify the midline dose profile.

To verify the results of "TBI Calc" program with Eclipse, a group of patients with different sizes were used for validation. Those patients were divided by different categories, adult and pediatric, with and without lung limit. The point doses calculated in Eclipse, which are near the patients' surface on umbilicus and the lung part, were compared with the *in vivo* measured doses. Also, the midline doses in center different body parts were compared with the prescription dose.

4.3 Results

4.3.1 Phantom with the Patient's Body Shape

A patient phantom, which contains the body (green line) and lung (yellow line), is created and shown in Figure 26. It is shown as three views (transversal, frontal, sagittal views) and beam eye view with the compensators added on head, neck, lung and lower legs. The remaining patients' phantoms were created using the same way. For the patient without lung limit, the phantom only involves the body structure, the whole phantom is water equivalent, which is shown in Figure 27.

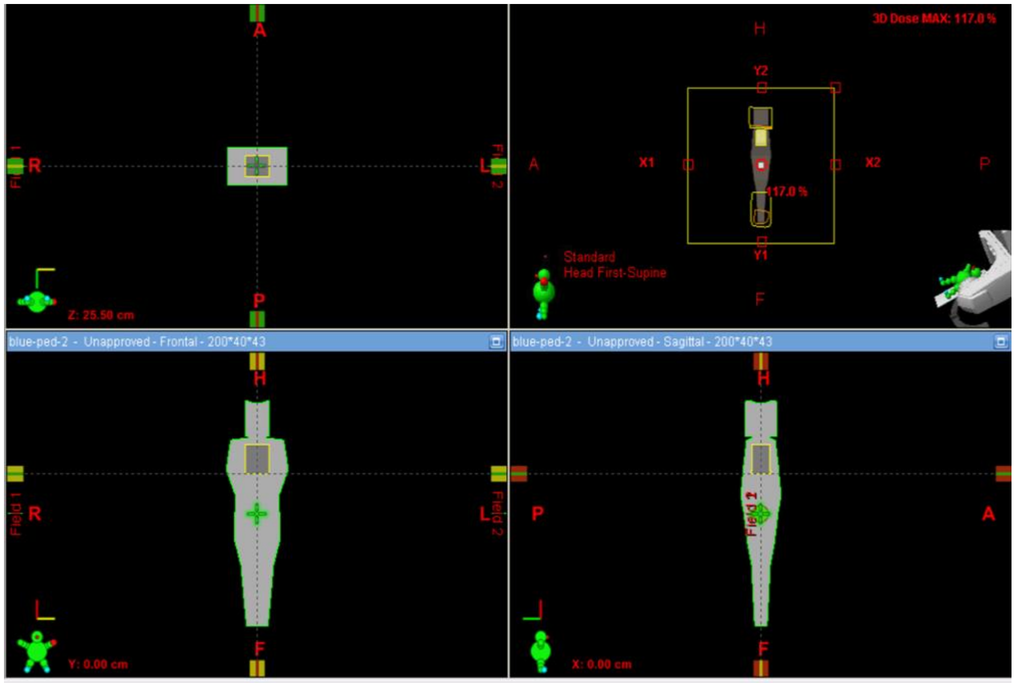

Figure 26: An example of pediatric patient phantom with lung limit in the Eclipse. Blocks are added on various parts, such as head, neck, lung and lower legs.

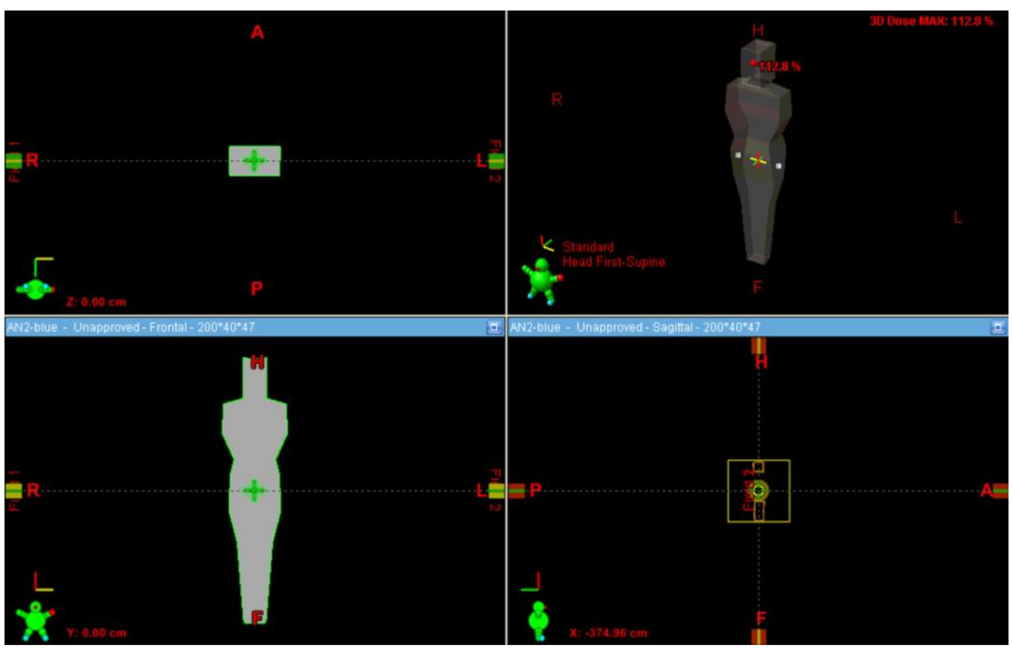

Figure 27: An example of adult patient phantom without lung dose limit in the Eclipse. The whole body is uniform.

4.3.2 Treatment Planning System Using Eclipse

15 patients were divided into 3 groups, adult patients without lung limit, adult patients with lung limit, and pediatric patients with lung limit. Table 12 shows the doses of adult patients without lung limit (prescribed dose is 200 cGy with single fraction) at umbilicus level and the differences with the *in vivo* measurement and prescription dose. It also contains the thickness of umbilicus in order to show their influence on dose accuracy. Table 13 shows the midline dose at the various anatomy sites and the percentage difference with the prescribed dose. For the patients with lung limit, the dose at the umbilicus level and lung are compared with the *in vivo* measurements, which are shown in the Table 14 and Table 16 for adult and pediatric patient, respectively. The calculated doses at the umbilicus level indicate they are matched better with the measured dose than the doses at the lung area. Table 14 and table 16 contain mid-mediastinum thickness, which is at lung level. Table 15 and Table 17 show midline dose at the reference sites and their comparison with the prescribed dose for adult (150 cGy with 9 fractions) and pediatric patients (165 cGy with 8 fractions) with lung limit, respectively.

For adult patients without lung limit, the doses calculated by Eclipse are always lower than the *in vivo* measured doses, however, the calculated doses have better agreement with the prescribed dose than measured doses. The midline doses at the head and umbilicus level agree better with prescribed doses than the doses at neck and lower legs.

The patients that have lung limit indicated different results with the patients without lung limit. Calculated dose is higher than the measured dose and prescription dose at lung and umbilicus levels. The midline doses at the head and umbilicus have smaller differences with the prescribed dose than the doses at the neck and lower legs as well.

Moreover, Table 18 and Table 19 show the mean value and standard deviation of the difference of point doses among Eclipse, *in vivo* measurement, and prescribed dose for umbilicus doses and lung doses respectively. Overall, the results describe that umbilicus doses agree better with *in vivo* measurement and prescription than lung dose. Table 20 demonstrates that mean value and standard deviation of the difference of midline doses between Eclipse and prescription. The results indicate that head and umbilicus have better agreement with prescription dose than neck, lung, and lower legs.

Table 12: Umbilicus dose for adult patient without lung limit. The results are compared with the prescription dose and *in vivo* measurement.

Adult Pt	*Cax thickness*	*Eclipse Cax dose (cGy)*	*% diff with prescription*	*In vivo measure (cGy)*	*% diff with prescription*	*% diff between Eclipse and measurement*
AN1	42	214.9	7.5%	229.9	15%	-7.5%
AN2	27	205.8	2.9%	208.2	4.1%	-1.3%
AN3	38	205.9	3.0%	211.9	6.0%	-3%
AN4	35.5	208.3	4.2%	209.5	4.8%	-0.6%
AN5	34	207.1	3.6%	217.9	9.0%	-5.4%

Table 13: Midline doses at the reference point for adult patient without lung limit. The results are compared with the prescription dose.

Adult Pt	*head*	*% diff*	*neck*	*% diff*	*Umbilicus*	*% diff*	*Lower legs*	*% diff*
AN1	205.2	2.6%	188.8	-5.6%	201	0.5%	203.8	1.9%
AN2	201	0.5%	180.6	-9.7%	201.6	0.8%	186.6	-6.7%
AN3	204.6	2.3%	185.4	-7.3%	200.2	0.1%	190.4	-4.8%
AN4	201.4	0.7%	186.6	-6.7%	200.2	0.1%	192.6	-3.7%
AN5	203	1.5%	175.4	-12.3%	202	1%	195.8	-2.1%

Table 14: Umbilicus and lung dose for adult patient with lung limit. The results are compared with the prescription dose and *in vivo* measurement.

Adult Pt	*Thickness (cm)*	*Eclipse dose (cGy)*	*% diff with prescription*	*In vivo measure*	*% diff with prescription*	*% diff between Eclipse and in vivo measure*
AY1	Cax:32.5	157.2	4.8%	144.6	3.6%	1.2%
	MM: 48.5	109.2	9.2%	101.8	1.8%	7.4%
AY2	Cax:41.5	159.4	6.3%	153.7	2.5%	3.7%
	MM:53.5	119.2	7.3%	109.4	-1.5%	8.8%
AY3	Cax:39	157.0	4.7%	152.8	1.9%	2.8%
	MM:49	117.4	5.7%	105.4	-5.1%	10.8%
AY4	Cax:30	155.8	3.9%	152	1.3%	2.6%
	MM:42	98.3	10.6%	84.5	-5%	15.6%
AY5	Cax:36	157.7	5.1%	155.9	3.9%	1.2%
	MM: 47	106.7	6.7%	100.2	0.2%	6.5%

Table 15: Midline doses at the reference point for adult patient with lung limit. The results are compared with the prescription dose.

Adult Pt	*head*	*% diff*	*neck*	*% diff*	*lung*	*% diff*	*Umbilicus*	*% diff*	*Lower legs*	*% diff*
AY1	153.2	2.1%	138.0	-8.0%	97.5	-2.5%	150.2	0.1%	142.9	-4.7%
AY2	154.2	2.8%	137.7	-8.2%	106.7	-4.0%	150.6	0.4%	146.6	-2.3%
AY3	154.4	2.9%	141.5	-5.7%	113.6	2.2%	147.3	-1.8%	145.7	-2.9%
AY4	153.8	2.5%	140.6	-6.3%	94.5	6.3%	149.3	-0.5%	150.3	0.2%
AY5	149.4	-0.4%	140.9	-6.1%	104.3	4.3%	148.9	-0.7%	144.9	-3.4%

Table 16: Umbilicus and lung dose for pediatric patient with lung limit. The results are compared with the prescription dose and *in vivo* measurement.

Ped Pt	*Thickness (cm)*	*Eclipse dose (cGy)*	*% diff with prescription*	*In vivo measure*	*% diff with prescription*	*% diff between Eclipse and in vivo measure*
PY1	Cax:21	171.4	3.8%	170	3.3%	0.5%
	MM:31	133.4	6.7%	119.5	-4.4%	11.1%
PY2	Cax:20	170.8	3.5%	162.3	-1.6%	5.1%
	MM:32	130.2	4.2%	120.5	-3.6%	0.6%
PY3	Cax:35.5	168.8	2.3%	168.7	2.2%	0.1%
	MM:49	131.2	5.0%	128.8	3%	2%
PY4	Cax:24.5	171.3	3.8%	162.5	-1.5%	5.3%
	MM:42	131.1	4.9%	129.8	3.8%	1.1%
PY5	Cax:28	169.0	2.4%	162.1	-1.8%	4.2%
	MM:40	134.8	7.8%	117.7	-5.8%	13.6%

Table 17: Midline doses at the reference point for pediatric patient with lung limit. The results are compared with the prescription dose.

Ped Pt	*head*	*% diff*	*neck*	*% diff*	*lung*	*% diff*	*Umbi licus*	*% diff*	*Lowe r legs*	*% diff*
PY1	170.8	3.5%	160.5	-2.7%	123.8	-0.9%	162.7	-1.4%	160.7	-2.6%
PY2	170.3	3.2%	155.1	-6.0%	124.1	-0.7%	162.4	-1.6%	165.1	0.1%
PY3	166.2	0.7%	159.1	-3.6%	120.8	-3.4%	161.7	-2.0%	159.6	-3.3%
PY4	166.8	1.1%	156.7	-5.0%	118.8	-5.0%	164.2	-0.5%	158.7	-3.8%
PY5	167.3	1.4%	157.1	-4.8%	124.6	-0.3%	164.2	-0.5%	157.6	-4.5%

Table 18: Mean value and standard deviation of the difference of point doses for umbilicus doses

No. of Pts	*Dose % diff at umbilcus*		
	Eclipse and prescription	Measurement and prescription	Measurement and Eclipse
15	4.1% $\pm$ 1.4%	3.2% $\pm$ 4.3%	0.6% $\pm$ 3.7%

Table 19: Mean value and standard deviation of the difference of point doses for lung doses

No. of Pts	*Dose % diff at lung*		
	Eclipse and prescription	Measurement and prescription	Measurement and Eclipse
10	6.8% $\pm$ 2.0%	-1.7% $\pm$ 3.6%	7.8% $\pm$ 5.2%

Table 20: Mean value and standard deviation of the difference of midline doses

No. of Pts	*Dose %diff along midline*				
	Head	Neck	Lung	Umbilicus	Lower legs
15	1.8% $\pm$ 1.1%	-6.5% $\pm$ 2.4%	-0.4% $\pm$ 3.7%	-0.4% $\pm$ 1.0%	-2.8%$\pm$ 2.2%

4.4 Discussion

The work in this part demonstrates that Eclipse can be used for TBI planning at Extended SSD. The Eclipse can calculate the dose distribution in the patient phantom, which provides more than several selected point doses and a full 3D dose distribution. Using Eclipse for TBI planning, it allows more detailed evaluation of the patient treatment plan. It is potential to use this method to predict the dose uniformity, which can eliminate the need for time-consuming *in vivo* dose measurement. However, there are some limitations of this work.

The patient phantoms are the combination of several rectangular phantoms, which are shaped by the limited measured dimensions data. Additionally, the patient phantoms were simplified to water-equivalent, except for lung section. The whole patient phantom is homogeneous, and the lung densities are the same for every patient. However, in reality, patients' bodies are irregular that are far from enough to describe them by those limited measured data. The tissue heterogeneity is not taken into consideration either. It has some influences on the dose calculation. The lung density always changes at different ages.[7] It is impossible to know the exact density of lung and other tissue due to lack of patient' whole body CT.

The volumes of patient phantoms are generally larger than the patient volumes due to the rectangular shape of each slice. Thus, it may result in more scatters, which increases the dose to the calculation points. Also, the center of the patient phantom is different with the center of patients. The centers of the phantoms were set at the midpoint of the patient phantom in order to cover the patient's body in the limited-range image set in the Eclipse. But, in the actual treatment, the center is the umbilicus level, which is away from the patient's middle. The difference of center point can influence the depth to the midline, thus influence the dose to the umbilicus. Patient's body position is not the same either. In the Eclipse, patient's phantom is straight without knee bending. However, patients lie on the couch in a bent knee position for better body coverage. The different positions can cause the dose difference between the calculation in Eclipse and *in vivo* measurement.

The midline doses are supposed to equal to the prescribed dose because the uncorrected MU is calculated on the basis of giving prescription dose to the reference points, which are the midline of head, neck, lung, umbilicus and lower legs. However, the neck doses for all patients show that the calculated dose in Eclipse are much lower than the prescription dose. It implies that the neck sections in the phantoms are not accurate. In addition, when adding the compensators to the neck in the beam eye view, it was hard to draw neck compensators by freehand in the beam eye view. There is no distinct boundary between neck and shoulder because almost the entire body has uniform density, and neck is a small section compared to the whole phantom, which accounts for the difference between calculated dose and prescribed dose at neck area.

For patients with lung limit, it demonstrates that the lung doses calculated by Eclipse is about 5% higher than the prescribed dose, and it also has a big fluctuation compared with the measured lung dose. The lung in patient's phantom is also a rectangular section, the shape is different from the actual lung, which is narrow at the top but broad concave shape on the bottom.[22] It is hard to describe the exact lung shape based on 5 data from the chest x-ray measurement. Moreover, the lung density is unknown, resulting in the inaccurate dose calculation compared with the measured dose.

4.5 Future Work

The commissioning tests in the Varian Eclipse show an ideal match with the TBI Databook, which inspires the further work of using Eclipse for TBI treatment planning. However, the results of the dose calculation for the reference points show that there are some improvements can be done in the future. The shapes and the dimensions of the lung and neck sections need to be improved in patient phantoms. The lung density also needs adjustment and take patients' ages into consideration, which influence lung density. Furthermore, if patient's whole-body CT is accessible, the dose calculation could be more precise than the patient phantom that we created using MATLAB. The results of whole-body CT should be closer to the measured dose during treatment. However, consider that it is unnecessary to add extra dose to patients, XCAT phantom can substitute whole-body CT, which is a computed-generated phantom that can modify various parameters and provides a virtual model of the patients' anatomy.[23]

5. Conclusions

Total body irradiation is usually performed at extended SSD beyond 400 cm in order to make the field size cover the patient's whole body in one large field. TBI treatments are performed by simple dose calculation based on measurement data at Duke University Medical Center. Whether dose uniformity within $\pm$10% is difficult to know in patient's body. This study provides a method that using treatment planning system (Eclipse) to calculate the dose distribution for TBI planning. However, extrapolation is required when using typical treatment planning system to calculate the dose at extended SSDs because the commissioning data is measured at standard SSD of 100 cm. Thus, this needs comprehensive validation.

This work comprises two main part, the commissioning test for extended SSDs in Eclipse and the validation of using Eclipse for total body irradiation planning. For the commissioning tests, dosimetric factors including absolute output at extended SAD, phantom scatter factors, off-axis ratios, TMRs, spoiler factors, and compensator transmission factors were calculated at the same geometry as TBI commissioning in Eclipse. They showed good agreement with TBI commissioning measurement in clinic range. The differences of the dosimetric factors calculated in Eclipse and in TBI commissioning data were all below 2% in clinic range, with most of them within 1 %. The results indicated that Eclipse is able to calculate dose at extended SSD.

For validating the TBI planning in Eclipse, patient phantoms approximating patient body sizes were created with MATLAB and imported into Eclipse. Then treatment plans were done in Eclipse using the same parameters as the results calculated by "TBI Calc" program. When comparing between *in vivo* measurement and Eclipse calculations, umbilicus dose showed better agreement than lung dose. Along the midline, doses at head and umbilicus agreed better with prescribed dose than doses at neck, lung, and lower legs, which illustrates that lung, neck, and lower legs parts of patient phantoms need to be more precise with the actual patient body size. And there are future works can be done to improve the dose accuracy.

This work demonstrates that Eclipse can used for TBI planning at extended SSD even extrapolate the commissioning data at standard SSD of 100 cm. Eclipse can calculate not only doses at reference points, but also full 3D dose distributions, which provides more detailed dose information than current treatment planning program. This work shows the potentiality of using Eclipse for TBI planning in the future.

References

1. Levitt, S. H., Purdy, J. A., Perez, C. A. & Vijayakumar, S. *Technical Basis of Radiation Therapy: Practical Clinical Applications*. (Springer, 2006).

2. Halperin, E. C., Brady, L. W., Perez, C. A. & Wazer, D. E. *Perez & Brady's Principles and Practice of Radiation Oncology*. (Lippincott Williams & Wilkins, 2013).

3. Halperin, E. C. *Pediatric Radiation Oncology*. (Lippincott Williams & Wilkins, 1994).

4. Khan, F. M. *The Physics of Radiation Therapy*. (Lippincott Williams & Wilkins, 2010).

5. AAMP Task Group 29. The physical aspects of total and half body photon irradiation. *American Insitute of Physics* (1986).

6. Beyzadeoglu, M. *et al.* Effect of Dose-Rate and Lung Dose in Total Body Irradiation on Interstitial Pneumonitis after Bone Marrow Transplantation. *The Tohoku Journal of Experimental Medicine* **202**, 255–263 (2004).

7. Van Dyk, J., Keane, T. J. & Rider, W. D. Lung density as measured by computerized tomography: implications for radiotherapy. *International Journal of Radiation Oncology*Biology*Physics* **8**, 1363–1372 (1982).

8. Khan, F. M., Williamson, J. F., Sewchand, W. & Kim, T. H. Basic data for dosage calculation and compensation. *International Journal of Radiation Oncology*Biology*Physics* **6**, 745–751 (1980).

9. Wong, J. Y. C., Filippi, A. R., Dabaja, B. S., Yahalom, J. & Specht, L. Total Body Irradiation: Guidelines from the International Lymphoma Radiation Oncology Group (ILROG). *International Journal of Radiation Oncology*Biology*Physics* **101**, 521–529 (2018).

10. Tyson, T. E., Podgorsak, M. B., Singh, A. K. & Wang, I. Z. Improved dose homogeneity using electronic compensation technique for total body irradiation. *Journal of Applied Clinical Medical Physics* **19**, 159–167 (2018).

11. Sánchez-Nieto, B., Sánchez-Doblado, F. & Terrón, J. A. A CT-aided PC-based physical treatment planning of TBI: a method for dose calculation. *Radiotherapy and Oncology* **42**, 77–85 (1997).

12. Eclipse™ Treatment Planning System. *Varian Medical Systems* Available at: https://www.varian.com/oncology/products/software/treatment-planning/eclipse-treatment-planning-system. (Accessed: 4th March 2019)

13. Travis, E. L., Peters, L. J., McNeill, J., Thames, H. D. & Karolis, C. Effect of dose-rate on total body irradiation: Lethality and pathologic findings. *Radiotherapy and Oncology* **4**, 341–351 (1985).

14. Wheldon, T. E. The radiobiological basis of total body irradiation. *Br J Radiol* **70**, 1204–1207 (1997).

15. Barker, C. A. & Yahalom, J. Chapter 18 - Total Body Irradiation. in *Clinical Radiation Oncology (Fourth Edition)* (eds. Gunderson, L. L. & Tepper, J. E.) 341-357.e7 (Elsevier, 2016). doi:10.1016/B978-0-323-24098-7.00018-6

16. Side effects of a stem cell or bone marrow transplant | Cancer Research UK. Available at: https://www.cancerresearchuk.org/about-cancer/cancer-in-general/treatment/bone-marrow-stem-cell-transplants/side-effects. (Accessed: 4th March 2019)

17. Ribas, M. *et al.* Midplane dose determination during total body irradiation using in vivo dosimetry. *Radiother Oncol* **49**, 91–98 (1998).

18. International Atomic Energy Agency. *Commissioning of radiotherapy treatment planning systems: testing for typical external beam treatment techniques : report of the coordinated research project (CRP) on development of procedures for quality assurance of dosimetry calculations in radiotherapy*. (International Atomic Energy Agency, 2008).

19. Hui, S. K., Das, R. K., Thomadsen, B. & Henderson, D. CT-based analysis of dose homogeneity in total body irradiation using lateral beam. *J Appl Clin Med Phys* **5**, 71–79 (2004).

20. Abraham, D., Colussi, V., Shina, D., Kinsella, T. & Sibata, C. TBI treatment planning using the ADAC pinnacle treatment planning system. *Med Dosim* **25**, 219–224 (2000).

21. Bloemen-van Gurp, E. J., Mijnheer, B. J., Verschueren, T. A. M. & Lambin, P. Total body irradiation, toward optimal individual delivery: dose evaluation with metal oxide field effect transistors, thermoluminescence detectors, and a treatment planning system. *Int. J. Radiat. Oncol. Biol. Phys.* **69**, 1297–1304 (2007).

22. Richard L Drake & Wayne Vogl. Gray's anatomy for students. in *Gray's anatomy for students* 167–174 (Churchill Livingstone/Elsevier).

23. Segars, W. P., Mahesh, M., Beck, T. J., Frey, E. C. & Tsui, B. M. W. Realistic CT simulation using the 4D XCAT phantom. *Medical Physics* **35**, 3800–3808 (2008).