A thesis

entitled

Dose Modification Factor Analysis of Multi-Lumen Brachytherapy Applicator with
Monte Carlo Simulation

by

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Submitted to the Graduate Faculty as partial fulfillment of the requirements for the
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December 2012

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July 2012

Multi-lumen applicators like the Contura (SenoRx, Inc.) are used in partial breast irradiation (PBI) brachytherapy in instances where asymmetric dose distributions are desired, for example, when the applicator surface-to-skin thickness is small ($<7\text{mm}$). In these instances, the air outside the patient and the lung act as a poor scattering medium, scattering less dose back into the breast tissue which affects the dose distribution. Many commercial treatment planning systems do not correct for tissue heterogeneity, which results in inaccuracies in the planned dose distribution. This deviation has been quantified as the dose modification factor (DMF), equal to the ratio of the dose rate at 1cm beyond the applicator surface, with homogenous medium, to the dose rate at 1cm with heterogeneous medium. This investigation intends to model the Contura applicator with the Monte Carlo N-Particle code (MCNP, Los Alamos National Labs), determine a DMF through simulation, and correlate to previous measurements. Taking all geometrical considerations into account, an accurate model of the Contura balloon applicator was created in MCNP. This model was used to run simulations of symmetric and asymmetric plans. The dose modification factor was found to be dependent on the simulated water phantom geometry, with cuboid geometry yielding a max DMF of 1.0664. The same

measurements taken using a spherical geometry water phantom gave a DMF of 1.1221. It was also seen that the difference in DMF between symmetric and asymmetric plans using the Contura applicator is minimal.

Acknowledgements

I would like to thank everyone here at UT for making the past two years great. I want to thank Dr. Parsai for being the leader of the group and always looking out for us. I would like to thank Dr. Pearson for his instruction in the clinic and his help with this project. I would like to thank Dr. Shvydka for her assistance with MCNP and Nick Sperling for allowing me to use the cluster and providing answers to all things UNIX. I also want to thank Dr. Feldmeier for being an excellent physician and having the patience to work with students and Dr. Dennis for his input on the diagnostic side of physics.

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Chapter 1

Introduction

Current statistics show that breast cancer will affect 1 in 8 women in their lifetime. With over 226,000 new cases in the past year, breast cancer is the most prevalent form of cancer in women.⁽¹⁾ While incidence is high, the mortality rate is relatively low at 17%. This is in part due to the many forms of treatment a patient can undergo. In the radiation therapy field there are two main forms of treatment: whole breast irradiation and partial breast irradiation. Each treatment option has its own advantages but both are clinically relevant forms of treatment.

1.1 Treatment Techniques

Whole breast irradiation (WBI) is a traditional technique in which a patient receives 180 cGy per day totaling 4500-5040 cGy over the course of approximately 5 weeks. This radiation regimen is delivered after a surgical procedure called a lumpectomy is performed. In a lumpectomy the tumor is removed from the breast along with a small tissue margin. This margin is examined microscopically by pathology to confirm no cancer cells are present. During the initial portion of the treatment the entire breast is treated along with the chest wall with opposed oblique fields. At the end of this

period a boost of 1000-2000 cGy would be delivered, targeting only the lumpectomy cavity. The boost treatment is usually either a single electron field or two wedged photon fields. While this type of treatment has proven successful in the past, the ability to spare normal tissue always remains a goal for a radiation oncologist.

Partial breast irradiation (PBI) is a radically different way to treat breast cancer. This method of treatment was developed as an alternative to the traditional surgical option of a mastectomy. In a mastectomy, all breast tissue is removed from the affected breast along with skin, areola, nipple, and sometimes part of the underlying chest wall. In a modified radical mastectomy most of the axillary lymph nodes are also removed. This procedure can be physically and emotionally difficult for many patients. PBI leaves a large portion of the breast tissue intact since only a lumpectomy is performed. There is also a high probability that the areola and nipple will remain after a lumpectomy. The goal of PBI is to spare normal tissue in the breast and treat only a margin around the lumpectomy cavity, where cancer is most likely to recur. This is most commonly accomplished using high dose-rate brachytherapy.

Historically, before treatment planning systems where dose distributions could be made, PBI was performed by implanting needles into the patient's breast. These needles would be inserted using general or local anesthetic and were used to guide the nylon catheters in which the source will travel. The needles would then be removed but the catheters would remain in the breast for the whole course of treatment. Unlike PBI techniques currently used, these implants would be followed by a course of external beam treatment.

The typical course of treatment is very different between PBI and WBI. A PBI course lasts just five days with treatments occurring twice a day, separated by at least 6 hours. This reduces the total radiation course from 6-7 weeks to 1 week, making it an attractive option for those who qualify. A prescription is generally 340 cGy to spherical PTV 1 cm from the balloon surface. The course is 10 fractions totaling 3400 cGy. The advantages of PBI in terms of total dose and time of the course of treatment are evident.

Only some patients will be eligible for PBI due to the surgical involvement and the course of the treatment. Some requirements include: the patient must be less than 60 years of age, the tumor must be ductal carcinoma in situ (DCIS) or invasive adenocarcinoma, the gross disease must be 3 cm or less in diameter, the patient must have an estrogen receptor analysis performed on the primary tumor, and, if the tumor is invasive, the axillary nodes must be staged.⁽⁸⁾ These criteria, developed by the Radiation Therapy Oncology Group (RTOG), were created for a study to observe differences in effectiveness of WBI versus PBI.

Chapter 2

HDR Brachytherapy

High dose-rate (HDR) brachytherapy is the most common method for delivering radiation in PBI. Brachytherapy, from the Greek *brakhys* meaning short, delivers radiation by using a very strong radioactive source, in this case ^{192}Ir , placed inside or very close to the patient. Iridium is one of the rarest naturally occurring elements in the earth's crust and is found in its stable forms of ^{191}Ir and ^{193}Ir . ^{192}Ir is produced from the stable isotope of ^{191}Ir by neutron bombardment, usually in a nuclear reactor, and decays with a half-life of 73.83 days to the stable isotopes ^{192}Pt and ^{192}Os . With over thirty gamma-ray energies and nine beta particle energies, ^{192}Ir has a complicated decay scheme. Only seven of the possible gamma-rays are of high enough intensity to be considered relevant. These gamma emissions range from 290-608 keV with an average of 380 keV.⁽⁴⁾

Natural or surgically created cavities are used to insert the source via catheter or specialized applicator to ensure the source will be adjacent to, or inside, the treatment site. This is advantageous because the dose falloff of a single source is very high, so only the close-lying tissue is given full dose and normal structures can be spared. The source used in HDR is highly radioactive, on the order of Curies, so special precautions must be made when using this modality. The most significant way in which the patient and staff

are protected is from the use of an HDR afterloader. The afterloader is a shielded machine that houses the source which is attached to the end of a wire made of Nitinol alloy which is a shaped memory alloy. To ensure that no staff are exposed to high levels of radiation, the source stays in the afterloader until the patient is prepared, the proper measurements are taken, and all staff are out of the treatment room. A computer controls the entire treatment process, sending the source out, dwelling the source at different positions, and retracting the source back into the afterloader unit. After a treatment is finished, the room is checked with a Geiger counter to confirm the source has retracted fully.

A major drawback in many of today's brachytherapy treatment planning systems is that no inhomogeneity corrections are taken into account. For some treatments, such as Fletcher implants or vaginal cylinders, this is not a concern because there is no air or bone near the treatment site. Assuming all tissue is water density (1 g/cm^3) for these treatments is an accurate approximation. However, for treatments like PBI where the lumpectomy cavity is close to the skin surface, not correcting for the lack of backscatter from air can cause significant differences in the treatment plan.⁽³⁾ The difference between the planning system and reality causes less dose to be delivered to the treatment volume. This could lead to recurrence when it was thought the breast was receiving adequate dose.

2.1 HDR Applicators

There are four different applicators commonly used for PBI: MammoSite and MammoSite ML (Hologic, Inc.), Contura (SenoRX, Inc.), and SAVI (Cianna Medical, Inc.). All of these applicators are designed to be implanted into a patient's breast and be

filled with saline or adjusted in order to occupy the volume of the lumpectomy cavity. Each has one or multiple lumens that the Iridium source will traverse.

The MammoSite and MammoSite ML are very similar. The only difference being that the MammoSite has a single central lumen, whereas the MammoSite ML has an additional 3 lumens surrounding the central lumen arranged at 120° intervals. The added lumens give the ML the ability to shape the dose and create an asymmetric dose distribution that a single lumen applicator is incapable of creating. Asymmetry is created by either decreasing or eliminating one or more lumens from the treatment plan. The reason for creating an asymmetric dose distribution will be discussed later. In both models the lumens are contained within a silicone balloon that is filled with saline and a small amount of radiographic contrast during treatment. The most common balloon sizes are 4-5 cm and 5-6 cm which encompasses volumes of 34-113 cm³.

Figure 2.1: MammoSite single lumen applicator

The Contura multi-lumen applicator will be the main focus of this paper. This applicator has four lumens surrounding the central lumen, each separated by 90°. These lumens have a greater degree of curvature than the MammoSite ML. The maximum

distance between the central and outer lumens is 5mm, occurring at the center of the balloon. Like the MammoSite models, the Contura is available in two sizes: 4-5 cm and 4.5-6 cm diameters. These sizes enable the Contura to fill to the same volumes as the MammoSite applicators. Unlike the traditional single lumen balloon, it is important to ensure that the Contura does not rotate between treatments due to the lack of cylindrical symmetry. This applicator also has a vacuum port which can be used to remove air pockets or edema from around the balloon after implantation.

Figure 2.2: Contura applicator

The SAVI (strut adjusted volume implant) applicator is truly unique in its design, markedly different than previously mentioned applicators. The SAVI comes with 6, 8, or 10 distal lumens surrounding a central lumen in which the Iridium source can pass.⁽²⁾ The higher number of lumens allows for a greater degree of dose asymmetry to be obtained. These lumens are not contained within a balloon like the Contura and MammoSite applicators. While the previously mentioned applicators are filled with saline before treatment, the SAVI is simply expanded, filling the cavity with air. The amount of curvature in the lumens is much higher than that of the Contura or MammoSite ML. This can introduce some problems, namely that the source may not be able to negotiate the

tight curve. If this were to happen, the source would encounter an obstruction when sent out of the afterloader and the planned treatment would not be able to be delivered. This is a known issue that has been seen at this and other institutions.

Figure 2.3: SAVI applicator, 9 lumens

As stated previously, the main reason to use the multi-lumen applicators listed above is to create an asymmetric dose distribution. An applicator like the SAVI is able to have a greater degree of asymmetry due to the larger number of outer lumens, and the increased curvature of the lumens. The amount of asymmetry in each applicator can be quantified by using points around each applicator and measuring the difference in dose the points achieve. Four measurement points were placed at cardinal directions 1 cm from the outside of each applicator. A symmetric plan would give the same amount of dose to each of these points. To create an asymmetric plan three of these points were held constant while changing the remaining point as much as possible. The percentage difference of the asymmetric point to the average of the other three points is then the maximum asymmetry the particular applicator can achieve. The maximum dose asymmetry the Contura and SAVI applicators can achieve are 14.7% and 40.2%,

respectively. The four points used for measurement and the dose distributions can be found in Figures 2.3 and 2.4.

Figure 2.4: Contura symmetric vs. asymmetric plans

Figure 2.5: SAVI symmetric vs. asymmetric plans

2.2 Radiation Backscatter

There are five ways in which photons can interact with matter: Raleigh scatter, photoelectric effect, Compton scatter, pair production, and photodisintegration. Of these five, photoelectric effect and Compton scatter are the two dominant processes in a clinical setting. Photoelectric effect is most important for photon energies less than 25 kV. It is highly dependent on the absorbing material's atomic number, making it most

useful for diagnostic purposes like computed tomography (CT). In CT and other imaging modalities, it is important to see the difference between materials with different densities, like bone and soft tissue. While energies up to around 150 keV are useful for imaging, it is not practical to treat cancer or other lesions in this energy range because almost all of the dose is absorbed in the first 2 mm of the skin. Historically, photons with energies from 10-30 kV were used in the treatment of skin cancers, eczema, and psoriasis. This type of therapy, known as Grenz rays, has been almost entirely replaced by electrons with their very short penetrating distance.

Any photons with energy higher than 25 kV and less than 10 MV will have a higher probability to interact by Compton scattering. In the megavoltage energy range, the depth of maximum dose increases, useful when treating disease found deeper than the patient's skin. This interaction is relatively independent of the atomic number of the scattering material, but is dependent on the electron density. Compton scattering occurs when a high energy photon interacts with an unbound (outer shell) electron of the absorber. Unbound in this case means the binding energy of the electron is much less than the energy of the incident photon. When the photon interacts with this electron, some energy is transferred causing the electron to be emitted at an angle θ . The incident photon scatters at an angle ϕ with less energy. Using conservation laws, a relationship can be found between the energy of the particles and the scattering angle.

Chapter 3

MCNP

The software used for these simulations was the Monte-Carlo N-particle transport code MCNP5 (Los Alamos National Laboratory, Los Alamos, NM). MCNP is a general-purpose, continuous-energy code capable of simulating neutron, photon, and electron transport.⁽⁹⁾ The code uses a three-dimensional geometry and can take into account multiple materials and sources. Unlike deterministic methods which find the average particle behavior, MCNP tracks individual particles as they are radiated from the source until they reach a terminal point, like being absorbed or escaping from the problem. During this process, interactions (photoelectric, Compton, etc.) occur, the outcomes of which are determined by sampling probability distributions. As the simulation follows the particle through its interactions, if new particles are created through Compton scattering, fission, etc., the newly produced particles are stored in a bin. Once the initial particle reaches its endpoint, the binned particles are recalled and simulated until the initial particle and all subsequently created particles are completed. This process repeats until the simulation runs the number of particles specified in the input. The output file is then written with all tally measurements and statistical data.

The MCNP input is separated into “cards” that make up the geometric and physical specifications of the simulation. The first step in generating a model is to create the surface card. This card is made up of geometric figures, including spheres, cylinders, cones, cubes, planes, etc., which are used to define the boundaries in space of the model. This card must be made accurately as it will define the dimensions and boundaries of the simulation. Out of these surfaces the cell card is developed. This card defines the volumes of interest in the model and is defined with surfaces from the previous step. The cell card is where materials and densities for the constituent parts of the model are referenced. In each cell the material number and density are declared.

The final card is the data card. In this card all the technical specifications for the simulation are defined. The “mode” is stated to determine neutron, photon, or electron transport. All materials used in the simulation must be created and described in the data card. MCNP uses nuclear data tables containing interaction data, cross-sections, thermal data, etc. so that simulations will reproduce original data as accurately as possible. These data tables are referenced by the types of materials contained in the input file. To create the materials, the atomic composition and the percentage of each component must be known. Materials are created in a *ZZZAAA* format, where *ZZZ* is the atomic number and *AAA* is the atomic mass number. For simulations run with ^{192}Ir , the material input would be 77192. This would be followed by a 1 to indicate that the source was pure Iridium. The composition of each material can be defined by unnormalized atomic fraction or mass fraction. The source definition (sdef) is also created in the data card. A source is determined by a number of factors, including cell number (CEL), position (POS), axis (AXS), radial distance from position (RAD), distance from position along the defined

axis (EXT), and energy (ERG). The cell number determines which user-defined cell the source will be. The position and axis definitions set up a coordinate system for the source. From this coordinate system the RAD and EXT definitions determine a volume in which the simulation will create particles. This should be as close as possible to the actual cell volume or the source efficiency will decrease, leading to longer run times. The energy definition, usually a distribution, states all particle energies along with relative probabilities of each energy. This data can be found in nuclear decay tables from sources such as the US Department of Energy. Appendix A is an example of an input file used with the Contura model.

Chapter 4

Methods and Materials

The main advantage of a multi-lumen PBI applicator is its ability to shape the dose into a distribution that is not symmetric. This could be important for small-breasted patients or those with a shallow lumpectomy cavity. In each instance, the patient may have a small balloon-to-skin distance, resulting in the RTOG-0413 standard of 5-7 mm to not be met. This criterion states that all cases with a distance ≥ 7 mm are acceptable and a distance of 5 mm is only appropriate if the skin receives $\leq 145\%$ of the prescription dose.⁽⁸⁾ The prescription dose is defined 1 cm from the balloon surface and is called the planning target volume (PTV). When planning with a PBI balloon, such as the Contura, one can decrease or eliminate the dwell times in the lumen closest to the skin surface to make the distribution asymmetric and give a smaller amount of dose to the skin. This could allow more patients to be eligible for PBI treatment. It is also important to pay attention to the limitations present in treatment planning systems. As stated previously, the lack of inhomogeneity corrections can lead to inaccuracies in the planned dose. In this case, the lack of backscatter would cause less dose to be given to the skin than is shown in the treatment planning system. If this error could be taken into account, more patients would pass the RTOG skin dose criterion which would make them eligible for treatment.

An example of the lack of density correction is shown below in Figure 4.1. If the planning system used density corrections there would be a stark difference in the isodose lines in water (gray) and air (black).

Figure 4.1: Example of no tissue inhomogeneity correction in treatment planning system

The purpose of this study is to quantify how much more dose the treatment planning system will show compared to the actual dose delivered for different amounts of backscatter present for the Contura multi-lumen PBI applicator. This was accomplished by creating MCNP simulations and measuring the dose 1 cm from the balloon surface with different amounts of backscatter present beyond the point of measurement. This data was compared to data taken with full backscatter, simulating current treatment planning systems. From this data a dose modification factor (DMF) was produced, defined as the ratio of the dose rate at the typical prescription distance of 1 cm from the balloon's

surface with full scatter, obtained using a water phantom, to the dose rate with a finite tissue thickness beyond the prescription line.⁽⁶⁾ The DMF is essentially the ratio of planned versus delivered dose when using a treatment planning system that does not take into account tissue heterogeneity.

Kassas et al. created Monte-Carlo simulations in order to study DMF using a single lumen MammoSite applicator. The balloon was in a spherical water phantom and a single dwell position at the center of the balloon was used. Simulations with varying amounts of backscatter were run by altering the water phantom's radius and were compared to a simulation with 30 cm of water beyond the measurement point (full backscatter). The area outside of the water phantom was modeled as dry air (75.53% N, 23.18% O, 1.28% Ar, and 0.0124% C) with a density of 0.001225 g/cm³. For small tissue thicknesses the difference in planned and delivered dose can be substantial, up to 13% for the largest balloon size and no backscatter.

In order to ensure that the MCNP parameters were the same and the models being made were sensible, the simulation from Kassas et al. was duplicated based on the parameters listed in the article. A comparison of the reproduced and previously taken data is shown in Figure 4.2.

Figure 4.2: Comparison of Kassas et al. to reproduction

The only point which has an appreciable difference is at 0 cm where the largest value of DMF occurs. The point at 0 cm shows the greatest percent difference, -0.43%, which could be due to differences in defining the location of zero (bottom/center/top of measurement chamber) or that this point has the greatest amount of fluctuation and highest uncertainty. Because the error was so low and all other points were nearly identical, the reproduction was considered a success and the next step of the study was undertaken: modeling and simulating the Contura applicator.

The initial model created was based on physical measurements taken using a Contura applicator and a traditional cuboid water phantom. Some assumptions were made with this model which will be shown to be reasonable. The first is the wire that the source is contained in which was not included in the simulations. Since all measurements taken will be relative and used to find the DMF, the small amount of attenuation from the wire

was assumed to be negligible. Using the previous model from Kassas et al. the effect of the stainless steel is shown in Figure 4.3.

Figure 4.3: Effect of steel cap on DMF

The largest difference in DMF between the simulations with steel and without steel is -0.0055%. The difference in the absolute dose from the two simulations was slightly higher but since all measurements are normalized to the full backscatter point this effect is minimized. From these results it was concluded that disregarding the wire was reasonable and would be done on all subsequent Contura models.

A model of the Contura applicator was created using Vised16D that accompanies MCNP5. Vised is a visual editor for MCNP and helps to visualize the geometry being created. The initial model had all 35 possible dwell positions, 5 lumens with 7 positions each, in a single simulation. Each of these positions had a weighting factor in order to duplicate the plan created and measured previously. In the plan delivery there would be a

single source that traverses each lumen separately, stopping at the 7 dwell positions for a certain period of time. Having all dwell positions in one simulation would add attenuation not present in the physical measurements. This effect was expected to be insignificant and will be discussed later on.

The Contura model consisted of a sphere with radius 2.2 cm to represent the balloon. Inside of the balloon 35 right circular cylinders were created to simulate the dwell positions of the applicator. Each source was 0.5 cm long with a radius of 0.017 cm and composed of pure ^{192}Ir . The photon energy spectrum of ^{192}Ir was taken from U.S. Department of Energy Radioactive Decay Tables.⁽⁵⁾ A small sphere with radius 0.17 cm was used as a measurement volume, simulating the ion chamber used in previous physical measurements. The BOX macrobody was used to create a water phantom with dimensions 40 cm by 40 cm by x, with x varying from 23.2 cm to 33.2 cm based on the depth to be measured. Everything within this box except the sources was made of water. This ignores the thin silicone wall of the balloon and nylon catheters which were assumed not to affect the dose. Outside of this box a 100cm^3 cube was used as air and to form a boundary for the simulation. A picture of the entire model is shown in Figure 4.4.

Figure 4.4: MCNP model with 2 cm of backscatter included

Figure 4.4 shows the outer, 100 cm³ box which defines the simulation boundary, with the light blue representing air. The inner rectangle is the water phantom with the Contura balloon and measurement volume within. Inside the balloon are the 35 dwell positions available to use in this type of applicator. A zoomed view of the balloon and dwell positions is shown in Figure 4.5 below.

Figure 4.5: Contura balloon with 3 of 5 lumens shown

Using Brachyvision (Varian Medical Systems, Palo Alto, California) and plans developed for the Contura applicator in previous research, a symmetric and asymmetric plan were produced. The difference between these two plans was that the asymmetric plan did not use the lumen nearest the measurement volume. The dwell times from these plans were then normalized to produce a weighting factor for each dwell position in the plan. When simulations were run, each dwell position produced the same number of particles and the outcome was multiplied by the weighting factor. This made the simulated plan an accurate duplication of the previously measured plan.

Each run was adjusted to minimize the uncertainty in measurements and to pass all of MCNP's statistical checks. This was done mainly by increasing the number of particles in the simulation. Increasing the number of particles factor (nps) in the input

caused the total time each simulation ran to increase. The number for most measurements was 5×10^7 particles which gave uncertainties $\ll 0.05\%$. Since the simulations were relatively simple, containing one source, a balloon and a measurement volume, the total time to run 35 simulations, one for each dwell position, was not unreasonably long.

Chapter 5

Results

The initial Monte-Carlo simulations were made to reproduce data from former members of the group at UTMC.⁽⁹⁾ Using the Contura model in the cuboid phantom previously mentioned, data with 0-10 cm backscatter was gathered and compared to previous measurements. This is shown in Figure 5.1.

Figure 5.1: Reproduced Contura applicator data in cuboid phantom

One can see that the above data shows a significant decrease in DMF for nearly all tissue depths. One drawback to the physical measurements taken is that they were

normalized to a depth of 10 cm, assuming that this depth was enough to provide full backscatter. Looking at the MCNP data one can see that this is not the case and that more backscatter should have been used. The Monte Carlo data shown here was normalized assuming that 50cm would provide full backscatter. This was not possible with the measurements due to limitations in the physical size of the water phantom used. This accounts for a difference of about 0.5% between the measurement and Monte Carlo simulations. Another error may be due to the fact that the experimental setup for the physical measurements could not be perfectly reproduced, as in a computer simulation. It was thought that small set up variations in the distance of the ion chamber above the balloon or in the water depth could have caused large variations in the DMF measurements. To test this, deliberate errors were introduced to the simulation. The position of the measurement volume and the level of water above the volume were changed in order to mimic potential errors that might have occurred during physical measurements. An error of 2 mm in these measurements was shown to cause an error of up to 0.3% in simulations. In an attempt to find the cause of the remaining error and to ensure our geometry was correct, our reproduction of the Kassas MCNP model was simulated in the cuboid water phantom geometry rather than a spherical phantom. The results of this simulation are shown in Figure 5.2.

Figure 5.2: Kassas et al. model in cuboid phantom

The above figure indicates that our Contura model is reasonable, with small deviations ($<1\%$) being seen due to the different applicators in the two simulations. The symmetric plan used for the simulations in Figure 5.2 was not expected to be significantly different than the simple, single dwell position MammoSite plan used by Kassas et al. Both plans were created by setting the prescription dose to a point 1 cm from the balloon surface. Although the Contura plan would be more complex, with 5 lumens and 35 dwell positions, both plans deliver the same dose to the same point. The only differences in DMF should then be caused by scattered dose originating from different points due to the increased number of dwell positions. To see how the water phantom geometry affects DMF, the Contura model was simulated in a spherical water phantom and compared to the simulations in a cuboid water phantom. This is shown in Figure 5.3.

Figure 5.3: Contura model in difference water phantoms

The large differences in DMF in Figure 5.3 demonstrate that the water phantom geometry used in the simulation is significant. A spherical water phantom yields higher values of DMF than a traditional cuboid phantom. This could be due to more total scattering volume present in the cuboid phantom simulation. The volume of the cuboid phantom was much larger than the sphere for all depths because only one side of the phantom changed for the different tissue depths. The cuboid volumes were over 60 times larger than the spheres used, a fraction of which contributed to the scatter dose in the detector. Figure 5.4 demonstrates this graphically.

Figure 5.4: Difference in scattering material for sphere and cuboid water phantoms

The differences in symmetric and asymmetric plans were also studied. The same data was used in each instance with the weighting factors changing to simulate each plan. In the asymmetric plan the central lumen and the lumen nearest the measurement point were not used. The data from the two simulations is shown in Figure 5.5.

Figure 5.5: Symmetric vs. Asymmetric DMF

There is no significant difference between symmetric and asymmetric simulations. This is expected because of the way the DMF is defined. Since all measurements are relative to full backscatter data, large differences to the absolute dose at the measurement point should not be seen in the DMF. Small deviations in Figure 5.5 ($<0.3\%$) were due to the symmetric and asymmetric plans producing different scatter contributions to the measurement volume.

Chapter 6

Summary and Conclusion

The MCNP models created and used were found to be reasonable by comparing data to previous results in Kassas et al. These simulations matched very well to DMF data found in their article. Simulations were created and run for the Contura multi-lumen applicator using different water phantom geometries. It was seen that the two geometries (spherical and cuboid) gave significant differences in DMF values. This can be attributed to the additional scattering material in the cuboid phantom. When interpreting these results it is important to consider which phantom best approximates the curve of the average breast. A normal breast, being curved but not spherical, would fall in between the two phantom geometries. Taking this into account, the lack of tissue inhomogeneity correction in treatment planning systems can produce plans in a phantom geometry that under-dose the PTV by up to 7-12%. In a radiation course like PBI, where the total dose is low compared to external beam treatments, this under-dosing could be significant and cause recurrence in some patients.

Significant differences in physical measurements and computer simulations were seen when comparing previous results made at UTMC. This was likely due to limitations in reproducing the setup accurately each time measurements were made and errors in

what was determined to be full backscatter. These factors created errors of up to 4% between physical and simulated measurements. Unlike taking measurements with an ion chamber and water phantom, a computer simulation will be set up exactly in the way that is specified every time a measurement is taken. This eliminates any setup error and allows data from different simulations to be compared directly.

PBI has become more popular in the recent past and will likely gain popularity in the future. Clinical studies have shown that it is a viable treatment option for those that qualify and can be much less physically and emotionally taxing on the patient. The results given in this paper can help make this treatment modality more accurate, increasing the cure rate and decreasing recurrence in women who choose this option for their treatment.

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Appendix A

c

c Start Cell Card

c

```

1  2 -22.42 -101
2  2 -22.42 -102
3  2 -22.42 -103
4  2 -22.42 -104
5  2 -22.42 -105
6  2 -22.42 -106
8  3  -1 -1 #1 #2 #3 #4 #5 #6 #7 #10 #11 #12 #13 #14 #15 #16 #17 #18
    #19 #20 #21 #22 #23 #24 #25 #26 #27 #28 #29 #30 #31 #32 #33 #34 #35
    #36 #37
7  2 -22.42 -107
10 2 -22.42 -501
11 2 -22.42 -502
12 2 -22.42 -503
13 2 -22.42 -504
14 2 -22.42 -505
15 2 -22.42 -506
16 2 -22.42 -507
17 2 -22.42 -201
18 2 -22.42 -202
19 2 -22.42 -203
20 2 -22.42 -204
21 2 -22.42 -205
22 2 -22.42 -206
23 2 -22.42 -207
24 2 -22.42 -301
25 2 -22.42 -302
26 2 -22.42 -303
27 2 -22.42 -304
28 2 -22.42 -305
29 2 -22.42 -306
30 2 -22.42 -307
31 2 -22.42 -401
32 2 -22.42 -402
33 2 -22.42 -403
34 2 -22.42 -404
35 2 -22.42 -405
36 2 -22.42 -406
37 2 -22.42 -407
41 3  -1 -6
42 0    8
43 1 -0.001225 7 -8
45 3  -1 -7 1 #41

```

c

c Start Surface Card


```

c
1    so 2.2
c
c central lumen
501   rcc -1.06 0 0 -0.5 0 0 0.017 $central #1
502   rcc -0.54 0 0 -0.5 0 0 0.017 $central #2
503   rcc -0.02 0 0 -0.5 0 0 0.017 $central #3
504   rcc 0 0 0 0.5 0 0 0.017 $central #4
505   rcc 0.52 0 0 0.5 0 0 0.017 $central #5
506   rcc 1.04 0 0 0.5 0 0 0.017 $central #6
507   rcc 1.56 0 0 0.5 0 0 0.017 $central #7
c
c +Z lumen
101   rcc -0.01 0 0.5 -0.4975 0 -0.05 0.017 $#3
102   rcc 0.01 0 0.5 0.4975 0 -0.05 0.017 $#4
103   rcc 0.5264 0 0.444 0.4952 0 -0.069 0.017 $#5
104   rcc -0.5264 0 0.444 -0.4952 0 -0.069 0.017 $#2
105   rcc -1.04 0 0.361 -0.4952 0 -0.069 0.017 $#1
106   rcc 1.04 0 0.361 0.4952 0 -0.069 0.017 $#6
107   rcc 1.55 0 0.28 0.4985 0 -0.0387 0.017 $#7
c
c -Z lumen
201   rcc -0.01 0 -0.5 -0.4975 0 0.05 0.017 $#3
202   rcc 0.01 0 -0.5 0.4975 0 0.05 0.017 $#4
203   rcc 0.5264 0 -0.444 0.4952 0 0.069 0.017 $#5
204   rcc -0.5264 0 -0.444 -0.4952 0 0.069 0.017 $#2
205   rcc -1.04 0 -0.361 -0.4952 0 0.069 0.017 $#1
206   rcc 1.04 0 -0.361 0.4952 0 0.069 0.017 $#6
207   rcc 1.55 0 -0.28 0.4985 0 0.0387 0.017 $#6
c
c -Y lumen
301   rcc -0.01 -0.5 0 -0.4975 0.05 0 0.017 $#3
302   rcc 0.01 -0.5 0 0.4975 0.05 0 0.017 $#4
303   rcc 0.5264 -0.444 0 0.4952 0.069 0 0.017 $#5
304   rcc -0.5264 -0.444 0 -0.4952 0.069 0 0.017 $#2
305   rcc -1.04 -0.361 0 -0.4952 0.069 0 0.017 $#1
306   rcc 1.04 -0.361 0 0.4952 0.069 0 0.017 $#6
307   rcc 1.55 -0.28 0 0.4985 0.0387 0 0.017 $#7
c
c +Y lumen
401   rcc -0.01 0.5 0 -0.4975 -0.05 0 0.017 $#3
402   rcc 0.01 0.5 0 0.4975 -0.05 0 0.017 $#4
403   rcc 0.5264 0.444 0 0.4952 -0.069 0 0.017 $#5
404   rcc -0.5264 0.444 0 -0.4952 -0.069 0 0.017 $#2
405   rcc -1.04 0.361 0 -0.4952 -0.069 0 0.017 $#1
406   rcc 1.04 0.361 0 0.4952 -0.069 0 0.017 $#6
407   rcc 1.55 0.28 0 0.4985 -0.0387 0 0.017 $#7
5    px 2
6    sz 3.2 0.17
7    so 6.2
8    so 30

c
c Start Data Card
c
mode p
c
m2  77192.      1  $Pure Ir-192 source

```

```

m3 1000.      2 $Pure water
    8000.      1
m1 7000.      -0.79 $Air
    18000.     -0.01 8000.      -0.2
c
imp:p      1 35r      0      1 1r      $ 1, 45
c
c Source Definition
c
sdef CEL=d1 POS=FCEL d2 AXS=1 0 0 RAD=FCEL d38 EXT=FCEL d74 ERG=FCEL d200 par 2
c
c Source weighting
c
si1 L 1 2 3 4 5 6 7 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29
    30 31 32 33 34 35 36 37
sp1 0.026013 0.026013 0.024803 0.026618 0.033273 0.013914 0.001815
    0.020569 0.020569 0.023593 0.022989 0.020569 0.013309 0.00121
    0.043557 0.042952 0.042347 0.042952 0.041742 0.040532 0.038717
    0.030853 0.032668 0.030248 0.028433 0.025408 0.028433 0.024803
    0.034483 0.035088 0.035088 0.033273 0.030853 0.032063 0.030248
c
c Position for each source
c
ds2 S 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29
    30 31 32 33 34 35 36 37
si3 L -0.259 0 0.478 $ center for spatially sampling of source 1
sp3 1 $ prob. distn for src 1 center
si4 L 0.259 0 0.478 $ center for spatially sampling of source 2
sp4 1 $ prob. distn for src 2 center
si5 L 0.777 0 0.41 $ center for spatially sampling of source 3
sp5 1 $ prob. distn for src 2 center
si6 L -0.777 0 0.41 $ center for spatially sampling of source 4
sp6 1 $ prob. distn for src 2 center
si7 L -1.288 0 0.328 $ center for spatially sampling of source 5
sp7 1 $ prob. distn for src 2 center
si8 L 1.288 0 0.328 $ center for spatially sampling of source 6
sp8 1 $ prob. distn for src 2 center
si9 L 1.814 0 0.26 $ center for spatially sampling of source 9
sp9 1 $ prob. distn for src 2 center
si10 L -1.3 0 0 $ center for spatially sampling of source 10
sp10 1 $ prob. distn for src 2 center
si11 L -0.776 0 0 $ center for spatially sampling of source 11
sp11 1 $ prob. distn for src 2 center
si12 L -0.245 0 0 $ center for spatially sampling of source 12
sp12 1 $ prob. distn for src 2 center
si13 L 0.275 0 0 $ center for spatially sampling of source 13
sp13 1 $ prob. distn for src 2 center
si14 L 0.80 0 0 $ center for spatially sampling of source 14
sp14 1 $ prob. distn for src 2 center
si15 L 1.3 0 0 $ center for spatially sampling of source 15
sp15 1 $ prob. distn for src 2 center
si16 L 1.83 0 0 $ center for spatially sampling of source 16
sp16 1 $ prob. distn for src 2 center
si17 L -0.259 0 -0.478 $ center for spatially sampling of source 17
sp17 1 $ prob. distn for src 2 center
si18 L 0.259 0 -0.478 $ center for spatially sampling of source 18
sp18 1 $ prob. distn for src 2 center
si19 L 0.777 0 -0.41 $ center for spatially sampling of source 19

```

```

sp19 1          $ prob. distn for src 2 center
si20 L -0.777 0 -0.41  $ center for spatially sampling of source 20
sp20 1          $ prob. distn for src 2 center
si21 L -1.288 0 -0.328  $ center for spatially sampling of source 21
sp21 1          $ prob. distn for src 2 center
si22 L 1.288 0 -0.328  $ center for spatially sampling of source 22
sp22 1          $ prob. distn for src 2 center
si23 L 1.814 0 -0.26  $ center for spatially sampling of source 23
sp23 1          $ prob. distn for src 2 center
si24 L -0.259 -0.478 0  $ center for spatially sampling of source 24
sp24 1          $ prob. distn for src 2 center
si25 L 0.259 -0.478 0  $ center for spatially sampling of source 25
sp25 1          $ prob. distn for src 2 center
si26 L 0.777 -0.41 0  $ center for spatially sampling of source 26
sp26 1          $ prob. distn for src 2 center
si27 L -0.777 -0.41 0  $ center for spatially sampling of source 27
sp27 1          $ prob. distn for src 2 center
si28 L -1.288 -0.328 0  $ center for spatially sampling of source 28
sp28 1          $ prob. distn for src 2 center
si29 L 1.288 -0.328 0  $ center for spatially sampling of source 29
sp29 1          $ prob. distn for src 2 center
si30 L 1.814 -0.26 0  $ center for spatially sampling of source 30
sp30 1          $ prob. distn for src 2 center
si31 L -0.259 0.478 0  $ center for spatially sampling of source 31
sp31 1          $ prob. distn for src 2 center
si32 L 0.259 0.478 0  $ center for spatially sampling of source 32
sp32 1          $ prob. distn for src 2 center
si33 L 0.777 0.41 0  $ center for spatially sampling of source 33
sp33 1          $ prob. distn for src 2 center
si34 L -0.777 0.41 0  $ center for spatially sampling of source 34
sp34 1          $ prob. distn for src 2 center
si35 L -1.288 0.328 0  $ center for spatially sampling of source 35
sp35 1          $ prob. distn for src 2 center
si36 L 1.288 0.328 0  $ center for spatially sampling of source 36
sp36 1          $ prob. distn for src 2 center
si37 L 1.814 0.26 0  $ center for spatially sampling of source 37
sp37 1          $ prob. distn for src 2 center
c
c Radial Distance
c
ds38 S 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60
      61 62 63 64 65 66 67 68 69 70 71 72 73
si39 0 0.05
sp39 -21 1
si40 0 0.05
sp40 -21 1
si41 0 0.05
sp41 -21 1
si42 0 0.05
sp42 -21 1
si43 0 0.05
sp43 -21 1
si44 0 0.05
sp44 -21 1
si45 0 0.05
sp45 -21 1
si46 0 0.02
sp46 -21 1

```

si47 0 0.02
 sp47 -21 1
 si48 0 0.02
 sp48 -21 1
 si49 0 0.02
 sp49 -21 1
 si50 0 0.02
 sp50 -21 1
 si51 0 0.02
 sp51 -21 1
 si52 0 0.02
 sp52 -21 1
 si53 0 0.05
 sp53 -21 1
 si54 0 0.05
 sp54 -21 1
 si55 0 0.05
 sp55 -21 1
 si56 0 0.05
 sp56 -21 1
 si57 0 0.05
 sp57 -21 1
 si58 0 0.05
 sp58 -21 1
 si59 0 0.05
 sp59 -21 1
 si60 0 0.05
 sp60 -21 1
 si61 0 0.05
 sp61 -21 1
 si62 0 0.05
 sp62 -21 1
 si63 0 0.05
 sp63 -21 1
 si64 0 0.05
 sp64 -21 1
 si65 0 0.05
 sp65 -21 1
 si66 0 0.05
 sp66 -21 1
 si67 0 0.05
 sp67 -21 1
 si68 0 0.05
 sp68 -21 1
 si69 0 0.05
 sp69 -21 1
 si70 0 0.05
 sp70 -21 1
 si71 0 0.05
 sp71 -21 1
 si72 0 0.05
 sp72 -21 1
 si73 0 0.05
 sp73 -21 1
 c
 c Distance from position along axis
 c
 ds74 S 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94

	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109
si75	-0.25	0.25													
sp75	-21	0													
si76	-0.25	0.25													
sp76	-21	0													
si77	-0.25	0.25													
sp77	-21	0													
si78	-0.25	0.25													
sp78	-21	0													
si79	-0.25	0.25													
sp79	-21	0													
si80	-0.25	0.25													
sp80	-21	0													
si81	-0.25	0.25													
sp81	-21	0													
si82	-0.25	0.25													
sp82	-21	0													
si83	-0.25	0.25													
sp83	-21	0													
si84	-0.25	0.25													
sp84	-21	0													
si85	-0.25	0.25													
sp85	-21	0													
si86	-0.25	0.25													
sp86	-21	0													
si87	-0.25	0.25													
sp87	-21	0													
si88	-0.25	0.25													
sp88	-21	0													
si89	-0.25	0.25													
sp89	-21	0													
si90	-0.25	0.25													
sp90	-21	0													
si91	-0.25	0.25													
sp91	-21	0													
si92	-0.25	0.25													
sp92	-21	0													
si93	-0.25	0.25													
sp93	-21	0													
si94	-0.25	0.25													
sp94	-21	0													
si95	-0.25	0.25													
sp95	-21	0													
si96	-0.25	0.25													
sp96	-21	0													
si97	-0.25	0.25													
sp97	-21	0													
si98	-0.25	0.25													
sp98	-21	0													
si99	-0.25	0.25													
sp99	-21	0													
si100	-0.25	0.25													
sp100	-21	0													
si101	-0.25	0.25													
sp101	-21	0													
si102	-0.25	0.25													
sp102	-21	0													
si103	-0.25	0.25													

```

sp103 -21 0      $ axial sampling weight for src2
si104 -0.25 0.25 $ axial sampling limits for src2
sp104 -21 0      $ axial sampling weight for src2
si105 -0.25 0.25 $ axial sampling limits for src2
sp105 -21 0      $ axial sampling weight for src2
si106 -0.25 0.25 $ axial sampling limits for src2
sp106 -21 0      $ axial sampling weight for src2
si107 -0.25 0.25 $ axial sampling limits for src2
sp107 -21 0      $ axial sampling weight for src2
si108 -0.25 0.25 $ axial sampling limits for src2
sp108 -21 0      $ axial sampling weight for src2
si109 -0.25 0.25 $ axial sampling limits for src2
sp109 -21 0      $ axial sampling weight for src2
c
c Energy probability
c
ds200 S 201 202 203 204 205 206 207 208 209 210 211 212 213 214 215 216 217
      218 219 220 221 222 223 224 225 226 227 228 229 230 231 232 233 234
      235
si201 L 0.2960 0.3085 0.3166 0.4681 0.5886 0.6044 0.6125
sp201 0.287 0.297 0.830 0.478 0.045 0.081 0.053
c
si202 L 0.2960 0.3085 0.3166 0.4681 0.5886 0.6044 0.6125
sp202 0.287 0.297 0.830 0.478 0.045 0.081 0.053
c
si203 L 0.2960 0.3085 0.3166 0.4681 0.5886 0.6044 0.6125
sp204 0.287 0.297 0.830 0.478 0.045 0.081 0.053
c
si205 L 0.2960 0.3085 0.3166 0.4681 0.5886 0.6044 0.6125
sp205 0.287 0.297 0.830 0.478 0.045 0.081 0.053
c
si206 L 0.2960 0.3085 0.3166 0.4681 0.5886 0.6044 0.6125
sp206 0.287 0.297 0.830 0.478 0.045 0.081 0.053
c
si207 L 0.2960 0.3085 0.3166 0.4681 0.5886 0.6044 0.6125
sp207 0.287 0.297 0.830 0.478 0.045 0.081 0.053
c
si208 L 0.2960 0.3085 0.3166 0.4681 0.5886 0.6044 0.6125
sp208 0.287 0.297 0.830 0.478 0.045 0.081 0.053
c
si209 L 0.2960 0.3085 0.3166 0.4681 0.5886 0.6044 0.6125
sp209 0.287 0.297 0.830 0.478 0.045 0.081 0.053
c
si210 L 0.2960 0.3085 0.3166 0.4681 0.5886 0.6044 0.6125
sp210 0.287 0.297 0.830 0.478 0.045 0.081 0.053
c
si211 L 0.2960 0.3085 0.3166 0.4681 0.5886 0.6044 0.6125
sp211 0.287 0.297 0.830 0.478 0.045 0.081 0.053
c
si212 L 0.2960 0.3085 0.3166 0.4681 0.5886 0.6044 0.6125
sp212 0.287 0.297 0.830 0.478 0.045 0.081 0.053
c
si213 L 0.2960 0.3085 0.3166 0.4681 0.5886 0.6044 0.6125
sp213 0.287 0.297 0.830 0.478 0.045 0.081 0.053
c
si214 L 0.2960 0.3085 0.3166 0.4681 0.5886 0.6044 0.6125
sp214 0.287 0.297 0.830 0.478 0.045 0.081 0.053
c

```

si215 L 0.2960 0.3085 0.3166 0.4681 0.5886 0.6044 0.6125
 sp215 0.287 0.297 0.830 0.478 0.045 0.081 0.053
 C
 si216 L 0.2960 0.3085 0.3166 0.4681 0.5886 0.6044 0.6125
 sp216 0.287 0.297 0.830 0.478 0.045 0.081 0.053
 C
 si217 L 0.2960 0.3085 0.3166 0.4681 0.5886 0.6044 0.6125
 sp217 0.287 0.297 0.830 0.478 0.045 0.081 0.053
 C
 si218 L 0.2960 0.3085 0.3166 0.4681 0.5886 0.6044 0.6125
 sp218 0.287 0.297 0.830 0.478 0.045 0.081 0.053
 C
 si219 L 0.2960 0.3085 0.3166 0.4681 0.5886 0.6044 0.6125
 sp219 0.287 0.297 0.830 0.478 0.045 0.081 0.053
 C
 si220 L 0.2960 0.3085 0.3166 0.4681 0.5886 0.6044 0.6125
 sp220 0.287 0.297 0.830 0.478 0.045 0.081 0.053
 C
 si221 L 0.2960 0.3085 0.3166 0.4681 0.5886 0.6044 0.6125
 sp221 0.287 0.297 0.830 0.478 0.045 0.081 0.053
 C
 si222 L 0.2960 0.3085 0.3166 0.4681 0.5886 0.6044 0.6125
 sp222 0.287 0.297 0.830 0.478 0.045 0.081 0.053
 C
 si223 L 0.2960 0.3085 0.3166 0.4681 0.5886 0.6044 0.6125
 sp223 0.287 0.297 0.830 0.478 0.045 0.081 0.053
 C
 si224 L 0.2960 0.3085 0.3166 0.4681 0.5886 0.6044 0.6125
 sp224 0.287 0.297 0.830 0.478 0.045 0.081 0.053
 C
 si225 L 0.2960 0.3085 0.3166 0.4681 0.5886 0.6044 0.6125
 sp225 0.287 0.297 0.830 0.478 0.045 0.081 0.053
 C
 si226 L 0.2960 0.3085 0.3166 0.4681 0.5886 0.6044 0.6125
 sp226 0.287 0.297 0.830 0.478 0.045 0.081 0.053
 C
 si227 L 0.2960 0.3085 0.3166 0.4681 0.5886 0.6044 0.6125
 sp227 0.287 0.297 0.830 0.478 0.045 0.081 0.053
 C
 si228 L 0.2960 0.3085 0.3166 0.4681 0.5886 0.6044 0.6125
 sp228 0.287 0.297 0.830 0.478 0.045 0.081 0.053
 C
 si229 L 0.2960 0.3085 0.3166 0.4681 0.5886 0.6044 0.6125
 sp229 0.287 0.297 0.830 0.478 0.045 0.081 0.053
 C
 si230 L 0.2960 0.3085 0.3166 0.4681 0.5886 0.6044 0.6125
 sp230 0.287 0.297 0.830 0.478 0.045 0.081 0.053
 C
 si231 L 0.2960 0.3085 0.3166 0.4681 0.5886 0.6044 0.6125
 sp231 0.287 0.297 0.830 0.478 0.045 0.081 0.053
 C
 si232 L 0.2960 0.3085 0.3166 0.4681 0.5886 0.6044 0.6125
 sp232 0.287 0.297 0.830 0.478 0.045 0.081 0.053
 C
 si233 L 0.2960 0.3085 0.3166 0.4681 0.5886 0.6044 0.6125
 sp233 0.287 0.297 0.830 0.478 0.045 0.081 0.053
 C
 si234 L 0.2960 0.3085 0.3166 0.4681 0.5886 0.6044 0.6125

sp234 0.287 0.297 0.830 0.478 0.045 0.081 0.053
c
si235 L 0.2960 0.3085 0.3166 0.4681 0.5886 0.6044 0.6125
sp235 0.287 0.297 0.830 0.478 0.045 0.081 0.053
c
si236 L 0.2960 0.3085 0.3166 0.4681 0.5886 0.6044 0.6125
sp236 0.287 0.297 0.830 0.478 0.045 0.081 0.053c
c Tally type
c
f6:p 41
c
c Number of particles
c
nps 1000000