FEASIBILITY OF OUT-OF-FIELD DOSIMETRY IN PHOTON, PROTON, AND NEUTRON THERAPIES USING A 3D-PRINTED PATIENT-SPECIFIC PHANTOM

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Abstract

Purpose: To test the feasibility of using a three-dimensional (3D) printed patient-specific phantom for out-of-field dosimetry.

Methods: Louisiana State University's laboratory fabricated a 3D-printed phantom of the whole body of a 5'4" female. To evaluate out-of-field dose produced between photon, proton, and neutron therapies out-of-field absorbed dose was measured in organs and structures at risk of debilitating effects for intracranial fields ranging in size from 2.8 x 2.8 cm^2 to 12.8 x 12.8 cm^2. Photon therapy was delivered using an Elekta linear accelerator in 6 MV and flattening-filter-free (6 FFF) modes, and a Varian Novalis Tx generated 6 MV fields. A clinical neutron therapy system delivered the neutron fields, and a clinical pencil beam scanning proton therapy system delivered the proton fields. The four out-of-field dose locations were at the thyroid, pacemaker, esophagus, and fetus.

Results: The modality with the lowest out-of-field absorbed dose was proton therapy followed by the Elekta 6 FFF, Elekta 6 MV, Varian 6 MV, and neutron therapy. For photon therapy, the Elekta 6 FFF produced the lowest out-of-field dose, and in comparison to the Elekta 6 MV, it was on average 25%, 15%, 25%, and 45% lower in the thyroid, pacemaker, esophagus, and fetus, respectively. In comparison to proton therapy, the out-of-field dose from the Elekta 6 FFF beam was on average 60% and 30% higher in the thyroid and pacemaker, respectively. Beyond the pacemaker, the out-of-field dose from proton therapy was indistinguishable from background for each field size.

Conclusion: We found that pencil beam scanning proton therapy offered the lowest out-of-field absorbed dose in comparison to 6 MV and 6 FFF photons and neutron modalities for intracranial fields. The study demonstrated the feasibility of using an inexpensive 3D-printed patient-specific

anthropomorphic phantom for out-of-field dosimetry. This is particularly important for quantifying the dose in organs, tissues, and electronics at risk for debilitating radiogenic effects.

Introduction

The goal of external beam radiation therapy is to deliver a prescribed quantity of radiation to a specified target while sparing the surrounding tissues to the greatest extent possible. Different forms of radiation are employed to deliver this dose, but most commonly seen are photons, electrons, neutrons, heavy ions, and protons. Each of these radiations deposit dose in its own unique fashion. Different secondary products are generated in the interactions of these radiations with components used to shape and direct the treatment beam.

Measurements and models used to predict how dose will be deposited are focused on the treatment of disease. They are intended to be used to validate that enough radiation has deposited energy in the target to produce a curative or palliative outcome, while sparing organs that could see negative side effects. Radiation is not confined to the treatment area, stray radiation deposits low doses surrounding the treatment location. Typically, the area receiving 50% of the maximum prescribed dose is defined as being in-field, whereas everything receiving less is classified as out-of-field (OOF). Dose inside the treatment volume has been thoroughly investigated and is well defined and understood. Moving farther away from the treatment field boundary produces discrepancies between measurements and treatment planning systems.[1] Because of this discrepancy when patients have a radiosensitive site outside the treatment field it is customary to perform a verification of the dose in that structure. This is especially important for children and patients that are pacemaker dependent or pregnant as small doses have been proven to produce negative outcomes.[2,3(p36)]

When estimating the mean organ dose for critical structures it is often difficult to estimate the distance from the radiation field edge due to the fact that during the treatment planning process when a computed tomography scan is acquired only the region surrounding the intended target is imaged. This causes difficulty in estimating and verifying mean organ dose for anatomy that is not contained within the image set. These verifications of dose are often performed on anthropomorphic phantoms based on a “standard human” as a stand-in for the patients anatomy, but can also be performed using research-based equations, specialized Monte Carlo codes or analytical models.[4]

Recently, to more accurately represent the anatomy of a patient under treatment researchers Craft and Howell created a postmastectomy high body mass index patient specific torso phantom using a 3D printer.[5] This phantom was constructed to investigate the ability of 3D printing to accurately construct a life size torso phantom. Yet to be investigated was the validity of constructing a 3D printed phantom for measurements performed outside the treatment field.

In this study we made use of a 5’4” anthropomorphic phantom printed three dimensionally by Louisiana State University to measure out-of-field (OOF) dose in the thyroid, pacemaker, esophagus, and fetus. This phantom was filled with 24 gallons of water and treated under conditions similar to a patient undergoing intracranial external beam radiation therapy. To compare between external beam treatment modalities left lateral intracranial fields ranging from 2.8x2.8 cm^2 to 12.8x12.8 cm^2 were applied.

Background

Photon Therapy

To deliver photon therapy of sufficient energy to cause radiobiologic damage high energy photon beams must be generated. These beams are typically created by the use of a linear accelerator (linac), which accelerates electrons through a vacuum tube using high-frequency electromagnetic waves. The electron beam impinges on a target, generating x-rays and heat through the bremsstrahlung process.[6] These x-rays are then focused on the patient for use in treating cancerous sites.

A linac is capable of generating beams of different maximum energies, each of which possess unique dose characteristics and specialized uses. Higher energy beams are more penetrating and can be used to treat tumors at greater depths. When using higher energies there are additional considerations for the shielding due to the production of unwanted neutrons generated from the photonuclear effect, beginning around 8 MV and becoming significant around 10 MV.[7] Because of these and other considerations most clinical beams are delivered using 6 MV. The typical maximum dose from a 6 MV beam lies at 1.5 cm when the source to surface distance is 100 cm and appropriate sized square field sizes are used.[8]

Historically in order to make these photon beams more useful their profile are shaped to form a uniform dose at known depths. The typical shape of a photon beam is determined by the energy spectrum generated when the electrons strike the target, resulting in a peak in the forward direction. To flatten out this peak a flattening filter is used to attenuate the beam and produce a uniform intensity across the treatment field. In newer generations of linacs this filter can be removed for treatment if a beam with an increased dose rate and peaked profile is desired. This is especially useful for treating small target sizes to a high dose as is typically seen in radiosurgery.[9]

The commercial design of linac manufacturers have slight but noticeable differences. The approach taken by Varian (Varian Medical Systems, Inc., Palo Alto, California) is to steer their electron beam through a 270-degree bending magnet, striking the target, and then passing through a primary collimator, collimating jaw(s), and a multileaf collimator (MLC) before the patient. Elekta (Elekta Oncology Systems, Crawley, United Kingdom) uses three bending magnets of 44, 44, and 112 degrees to shape their electron beam. This is followed with a primary collimator, single diaphragm or jaw, and a set of MLC's before reaching the patient.[10]

OOF dose in photon therapy is comprised of the contributions from patient scatter (scatter events that happen inside the patient), collimator scatter (scatter events that occur inside the treatment head), head leakage (photons that travel through the treatment head), and if the treatment energy is above 8 MV neutron generation. These beams must be regulated outside of the treatment field to reasonable levels laid out by governing bodies (1/1000 primary beam dose at 1 meter from the treatment head).[11] In-field radiation has an approximate average energy of 1/3 that of the maximum treatment energy, while head leakage is high energy, patient scatter and collimator scatter have undergone scattering events that result in a lower energy.[12]

Collimator scatter and patient scatter have variation depending on beam energy, field size, and collimation and result in different dose contribution with distance from the field edge. Within 20 cm of the treatment field patient scatter is the dominant source of OOF dose, head leakage takes over after 20 cm while collimator scatter makes up roughly 20% of dose no matter the distance from the treatment field. Removing the flattening filter from the beam results in a reduction in head leakage and collimator scatter, but has little impact on the patient scatter contribution for OOF dose.[12]

Proton Therapy

In proton therapy high energy protons are used to deliver radiation doses to tissue. The benefit of proton therapy over photon therapy is the finite range of a charged particle. With this finite range it is possible to have very steep distal dose falloff, minimizing dose downstream to at risk structures.[13] To generate these beams a synchrotron or cyclotron must be used as a source of proton acceleration.[14] Proton beams with a maximum treatment energy of 230 MeV (although synchrotrons can go higher) are capable of being generated with the equipment used for this study.

The Seattle Cancer Care Alliance (SCCA) Proton Therapy Center at which measurements were taken uses a cyclotron to accelerate their proton beam line (Ion Beam Applications, Louvain-La-Neuve, Belgium). This system employs an isochronous normally conducting cyclotron to accelerate protons. To isolate protons, hydrogen gas molecules are stripped of their electrons, leaving a proton which can then be accelerated up to 230 MeV for patient treatment after passing through an energy degrader. In order to cover the target the proton beam is magnetically steered to scan the beam over the target laterally at a depth specified by the energy, this deposits dose in "layers". Once a layer is completed, energy is shifted to scan the next layer. This process is repeated until the entire target is covered. This technique is called pencil beam scanning (PBS).

The two main sources of scattered radiation in proton therapy are the neutrons generated inside the treatment beamline (external neutrons), and those generated inside the patient (internal neutrons). Protons beams can be formatted into the shape of the treatment site in two primary ways: passively scattered and pencil beam scanning. In passive scattering proton therapy, material placed in the beamline is used to scatter the proton beam laterally in order to cover the target. Using material in the beamline acts as a source of external neutron generation through nuclear interactions. Using magnetically steered beams cuts down on external neutron production. This significantly reduces the absorbed dose contribution to nontarget sites over earlier systems because the majority of neutrons are occurring because of internal neutron generation.[15,16] These stray radiations are important because neutrons are more radiobiologically damaging than other radiations, and are of considerable concern to patients' long term health.[17]

Neutron Therapy

There is only one fast neutron therapy system currently treating patients in the United States. The Clinical Neutron Therapy System was built in 1984 at the University of Washington school of Medicine in Seattle, Washington. In order to generate fast neutrons a Scanditronix MC-50 cyclotron which produces 50.5 MeV protons impinge on a 10.5 mm thick beryllium target to produce neutrons through a “stripping” interaction.[18] This system is equipped with a 150 cm source to axis isocentric gantry and 40 leaf MLC for beam shaping. Percentage depth dose curve for in-field radiation is similar to a 6 MV photon beam, with a 10x10 cm^2 field having a maximum dose at 1.7 cm. Neutron therapy has primarily been shown to be effective at treating highly radioresistant tumors, such as those seen in the salivary gland.[19]

In addition to the neutron beam, additional byproducts are created by the interactions of the beam with the collimation, patient, and head of the machine and deposit dose in and outside the treatment field.[20] Neutrons move from the fast to thermal spectrum through interactions with hydrogenous materials inside the treatment vault, experiencing increasing nuclear interactions with the mediums as they thermalize. These interactions can result in additional products such as gammas, x-rays and heavy ions.

Radiation Detectors

Radiation dose is commonly measured using ionization chambers. These chambers contain an active volume of air or gas and are available in a wide variety of configurations. For most chambers a voltage bias is applied between the inner chamber wall and central electrode of the chamber. When radiation interacts with the chamber wall, or gas, charge carriers are liberated by ionization events. These charge carriers move across the active chamber volume and are collected by the central electrode. This collected charge can then be read out via an electrometer. By irradiating a chamber under known reference conditions, a conversion between dose and charge collected may be obtained.

In this study we rely on the Bragg-Gray cavity theory to establish the dose delivered to an ionization chamber which was related to the dose the medium was receiving.[21] For this theory to be applicable there are several assumptions that are made. First, that the cavity volume must not disturb the charged particle field and is smaller than the range of the charged particles. The second condition is that charged particles entering the cavity do not stop inside it. There are other conditions proposed by modern authors, but most rely on these assumptions as a starting point.

By assuming that the number of charged particles entering and leaving the detector is at an equilibrium it is possible to use a ratio of the energy loss per unit path length (stopping power) of the material outside the detector to that comprising the active volume of the detector. By multiplying by this stopping power ratio it is possible to determine what the dose is to the medium immediately surrounding the ionization chamber from the dose delivered to the chamber.

The charge collected by different radiotherapy modalities is deposited by various charge creating products. With photon therapy, below 8 MV the primary charge carriers set in motion are electrons. In particle therapy there is the possibility for generation of electrons, protons, alphas, gamma rays, recoil nuclei, and fragment products. Of these we are only capable of detecting the ions. These products can be collected themselves, or go on to cause additional interactions which can be collected by the detector.[22]

3D printing

3D printing can be used to generate almost any conceivable structure. Printers range in price from hundreds, to hundreds of thousands of dollars. Most filaments are plastic based, although some have the ability to print using metals, ceramics, or even concrete. Models are first constructed in 3D software where printing instructions are generated. Next the filament is prepared and laid onto the print bed under a set flow rate, nozzle temperature, and print speed. When a layer has been constructed the print nozzle moves vertically and begins laying the next slice. This process is repeated until all slices are completed and a finished product is rendered.

In radiation therapy 3D printing is becoming more accessible, as of recently its capabilities are beginning to be investigated for clinical applications. One such application has been investigated by Howell and Craft who were able to print a patient's abdominal anatomy and study percentage depth dose curves in polylactic acid filament blocks.[5] To date there has not been any investigations for a whole body 3D printed phantom for whole body OOF dosimetry.

Manuscript:

Feasibility of out-of-field dosimetry in photon, proton, and neutron therapies using a 3D-printed patient-specific phantom

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Introduction:

External beam radiation therapy is a safe and effective means of treating a wide range of debilitating diseases. Its clinical use has grown substantially alongside other treatment methods over the last century.[23] Children that have been treated with external beam radiotherapy are now living longer disease free lives.[24] This increased lifespan post irradiation allows for complications that would have in the past, gone unseen. A portion of these secondary complications occur in areas that were not the focus of treatment.[25] The treated volume is considered as tissues that are receiving at least 50% of the maximum radiation dose.[26] This 50% isodose surface creates a boundary separating tissues that are contained by the radiation field (in-field) and out-of-field (OOF). The optimum use of in-field radiation is to treat the diseased tissue while at the same time minimizing the dose to healthy tissues that lie both inside and outside the treatment field. Minimizing this OOF dose is always a concern due to the negative potential outcomes associated with radiation, such as a secondary cancer.[27] OOF dose becomes especially important when the patient is pregnant or pacemaker dependent because the nature of these radiosensitive sites. Therefore, it is important to be able to accurately quantify OOF dose when complications are a concern.

Estimation of OOF absorbed dose contribution from external beam radiation therapy is a difficult process. As it is of low-dose compared to the therapeutic dose it is commonly a secondary concern in overall patient treatment. For that reason treatment planning systems focus on accurately calculating absorbed dose near sites of treatment delivery. This results in poor estimates of absorbed dose outside the treatment volume.[1] Additional difficulties arise with the fact that most patients only receive a computed tomography (CT) scan of the region of anatomy intended to be treated. This causes difficulty with estimating absorbed dose contribution to critical structures that may lie outside the planning CT. As a solution when OOF measurements are required most clinics use either water equivalent blocks to simulate the extent of the patient, or modify existing phantoms to more closely suit their needs.[28] These are not ideal circumstances as most patients do not accurately reflect the flat surfaces and generalized phantoms commonly used. Craft and Howell were able to create a patient specific torso phantom using an in-house 3D printer which was then able to be used for dosimetric measurements.[5] Yet to be investigated was the validity of OOF dosimetric measurements using a whole-body 3D printed anthropomorphic phantom.

The purpose of this study is to determine the feasibility of using a 3D printed anthropomorphic phantom created by Louisiana State University for OOF dosimetric measurements. In order to establish if this is a valid method for estimation of OOF dose we applied intracranial fields ranging from 2.8 x 2.8 cm^2 to 12.8 x 12.8 cm^2 using external beam photon, proton, and neutron therapy systems and measured the absorbed OOF dose at the locations of the thyroid, pacemaker, esophagus, and fetus.

Materials and Methods:

CT Simulation of 3D printed Phantom

The 3D printed anthropomorphic phantom shell was constructed by Louisiana State University using a light scan of a 5'4" research subject. A commercial 3D printer (BigRep ONE, BigRep GmbH, Berlin, Germany) constructed the phantom shell from Polylactic Acid filament in sections that were then friction welded together and coated in a liquid latex to ensure water tightness. A half-inch diameter polyvinyl chloride (PVC) tube was imbedded along the central axis of the phantom to allow for a detector to be placed inside the phantom.

CT simulation of the phantom was performed at the Seattle Cancer Care Alliance proton center. Prior to use, the phantom was placed on the treatment couch and filled with water. Isocenter (labeled "A" in **Figure 1**) was established to localize the intracranial fields and accurately position the detector within the phantom. Isocenter was determined to be around the intersection of the plane of ears, nose and PVC pipe. After acquiring a whole-body scan of the phantom, patients with similar stature were compared to the phantom to approximate detector locations for the thyroid, esophagus, fetus, and pacemaker.

Figure 1: 3D printed phantom

Photograph of the 3D printed phantom. Labeled are the approximated detector locations for the Isocenter (A), Thyroid (B), Esophagus (C), Fetus (D), and Pacemaker (E)

External beam radiation therapy

Each external beam radiation therapy was delivered under similar conditions. Left lateral (gantry angles of 90 degrees) intracranial fields of 2.8x2.8 cm^2, 5.3.x5.3 cm^2, 7.8x7.8 cm^2, 10.3x10.3 cm^2, and 12.8x12.8 cm^2 were delivered. OOF absorbed dose (***D***) was normalized to a prescribed dose ($\boldsymbol{D_{Rx}}$) of 100 cGy at isocenter for each field size and treatment modality. All data at thyroid, esophagus, and fetus were collected at depth within the PVC pipe, whereas the pacemaker measurements were taken using buildup caps that simulated a tissue depth of approximately 5 mm.

Photon therapy

Photon therapy was delivered at Oregon Health & Science University (OHSU) using two different commercial medical linear accelerators. The Varian Novalis Tx, (Varian Medical Systems, Inc., Palo Alto, California and Brainlab, Munich, Germany) and Elekta Versa HD (Elekta Oncology Systems, Crawley, United Kingdom) were used to generate 6 MV intracranial fields. In addition, the Elekta Versa HD was used to produce 6 MV flattening filter free (FFF) fields (These FFF fields remove the flattening filter, typically in place to produce a uniform beam profile at 10 cm depth, resulting in a peaked profile along with higher dose rate). Treatment was delivered with the collimator positioned at 0 degrees on each machine, gantry at 90 degrees, and a source to axis distance of 100 cm. On the Novalis Tx, MLCs were retracted while delivering. For the smallest field size of $2.8x2.8cm^2$, to check detector placement at isocenter, megavoltage port films were taken. Radiation was detected using a PTW microDiamond (Type 60019, PTW-Freiburg, Freiburg, Germany) detector for small fields at isocenter and a PTW ion chamber (Type 30011, PTW-Freiburg, Freiburg, Germany) which was used for all additional field sizes at isocenter and OOF measurements. Additional monitor units were delivered at sites that were farther from the field edge to allow for added signal acquisition in order to better distinguish signal from background.

Neutron therapy

Neutron therapy was delivered at the Clinical Neutron Therapy System at the University of Washington. A tissue equivalent ionization chamber (Wellhoffer IC-30, Ion Beam Applications, Louvain-La-Neuve, Belgium) was used to measure both in field and OOF $\boldsymbol{D/D_{Rx}}$ contribution with a methane-based tissue equivalent fill gas. Another tissue equivalent ionization chamber with a methane-based tissue equivalent fill gas (IC-17, Far West Technology, Inc., Goleta, California) was used to validate daily beam output and cross-calibrate the IC-30 for $\boldsymbol{D/D_{Rx}}$ under daily output setup conditions. Each field was delivered at a source to axis distance of 150 cm and gantry angle of 90 degrees.

Proton therapy

Proton therapy was delivered at Seattle Cancer Care Alliance Proton Therapy Center (SPTC), using a 90 degree fixed beamline pencil beam scanning (PBS) system (Ion Beam Applications, Louvain-La-Neuve, Belgium). A tissue equivalent ionization chamber (Wellhoffer IC-30, Ion Beam Applications, Louvain-La-Neuve, Belgium) was used to measure OOF $\boldsymbol{D/D_{Rx}}$ contribution with a methane-based tissue equivalent gas.[29] In-field measurements were performed using a microdiamond detector for all field sizes. Because of the use of inverse planning at this facility a treatment plan was created in the treatment planning system (Raystation 6 (Version 6.1.1.2), RaySearch Laboratories AB, Stockholm, Sweden) for fields of 5.3x5.3x10 cm^3, 7.8x7.8x10 cm^3, and 10.3x10.3x10 cm^3. The detector was positioned at isocenter which corresponded to a source to axis distance of 210.7 cm using a maximum beam energy of 170 MeV and Spread-out Bragg Peak of 10 cm.

Figure 2: Phantom in treatment position

Photograph of 3D printed phantom on treatment couch after being filled with water and before being aligned for treatment with Pencil Beam Scanning proton therapy.

Results

Figure 3 shows the OOF $\boldsymbol{D/D_{Rx}}$ values taken using photon, proton, and neutron external beam radiation therapies at the sites of the thyroid, pacemaker, esophagus and fetus. For all modalities OOF $\boldsymbol{D/D_{Rx}}$ decreased with distance from the field edge. OOF $\boldsymbol{D/D_{Rx}}$ was lowest on average for PBS proton therapy, followed by Elekta Versa HD 6 FFF, Elekta Versa HD 6 MV, Varian Novalis Tx 6 MV, and neutron therapy. For proton and photon therapies there was a higher OOF $\boldsymbol{D/D_{Rx}}$ associated with larger field sizes, and the inverse occurred for neutron therapy.

Proton therapy resulted in the lowest OOF $\boldsymbol{D/D_{Rx}}$ at every site evaluated, and for every field size. The modality with the next closest OOF $\boldsymbol{D/D_{Rx}}$ was the Elekta Versa HD 6 FFF. Comparing these two modalities, proton therapy $\boldsymbol{D/D_{Rx}}$ for 5.3x5.3x10 cm^3 fields was 80% lower in the thyroid and 40% lower in the pacemaker location, 7.8x7.8x10 cm^3 was 50% lower in the thyroid and 20% lower in the pacemaker, and 10.3x10.3x10 cm^3 was 50% lower in the thyroid and 30% lower in the pacemaker. Smaller field sizes showed the greatest reduction in OOF D/D_{Rx} versus the larger three field sizes. In proton therapy for locations beyond the pacemaker the ability to distinguish D/D_{Rx} from background was unmeasurable.

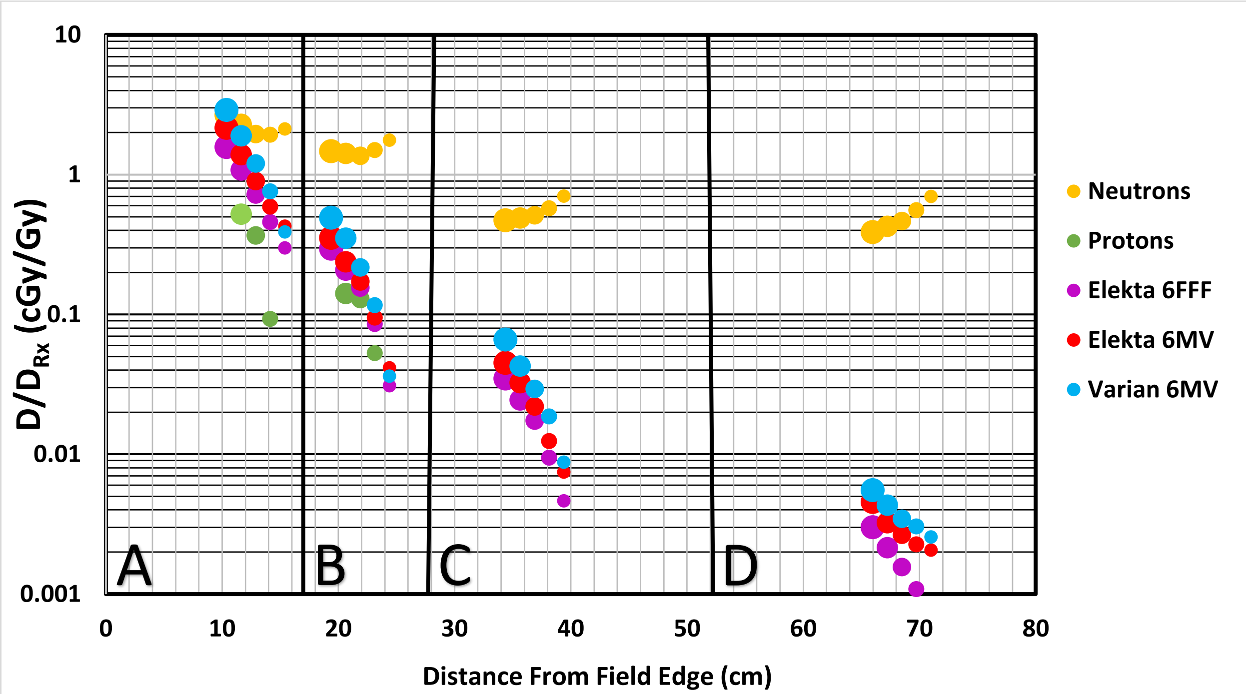

Figure 3: D/D_{Rx} vs Distance from field edge

Graph of absorbed dose per dose prescribed (D/D_{Rx})(cGy/Gy) versus distance (cm) from the field edge for 6 MV Elekta 6 FFF (purple), 6 MV Elekta (red), 6 MV Varian (blue), proton (green), and neutron (yellow) external beam therapies. Larger data points indicate a larger field size (12.8x12.8, 10.3x10.3, 7.8x7.8, 5.3x5.3, 2.8x2.8 cm^2). Solid black lines denote the general location of Thyroid (A), Pacemaker (B), Esophagus (C), and Fetus (D).

Among photon therapy the Varian Novalis Tx showed the highest OOF D/D_{Rx} on average. Comparing the 6 MV data for the Varian and Elekta machines, the Elekta Versa HD 6 MV D/D_{Rx} was lower by 20% in the thyroid, 20% in the pacemaker, 25% in the esophagus, and 25% in the fetus compared to the Varian Novalis Tx 6 MV. The different modes available on the Elekta Versa HD displayed difference as well, with the 6 FFF having a lower OOF D/D_{Rx} than the 6 MV by 25% in the thyroid, 25% in the esophagus, 15% in the pacemaker, and 45% in the fetus. For small field sizes progressing farther away from the field edge there showed a lower OOF D/D_{Rx} for 6 FFF measurements as opposed to 6 MV data. This became more pronounced when in the fetus region.

Neutron therapy had the highest OOF $\boldsymbol{D/D_{Rx}}$ among all treatment modalities following a similar trend to that of photon and proton therapies, with dose decreasing rapidly at areas near to the field edge but then leveling off at a constant $\boldsymbol{D/D_{Rx}}$ at distances far from the field edge. This dose falloff at distance was more gradual than other treatment modalities, and resembled a constant value dependent on field size, with smaller fields having a higher OOF $\boldsymbol{D/D_{Rx}}$.

Discussion

In this study we demonstrated the feasibility of measuring OOF $\boldsymbol{D/D_{Rx}}$ for external beam radiation therapy in a patient specific 3D-printed anthropomorphic phantom. We found that proton therapy resulted in the lowest overall OOF $\boldsymbol{D/D_{Rx}}$, followed by Elekta Versa HD 6 FFF, Elekta Versa HD 6 MV, Varian Novalis Tx 6 MV, and finally neutron therapy. For all treatment modalities investigated OOF $\boldsymbol{D/D_{Rx}}$ was shown to vary with field size and distance from the field edge.

In photon therapy OOF $\boldsymbol{D/D_{Rx}}$ was shown to vary on average by 20% between 6 MV Varian Novalis Tx and 6 MV Elekta Versa HD measurement, with the Elekta Versa HD having the lower $\boldsymbol{D/D_{Rx}}$. Shielding design, collimator configuration, and machine age differences each attributed to these differences seen in OOF $\boldsymbol{D/D_{Rx}}$. An average of 30% higher OOF $\boldsymbol{D/D_{Rx}}$ measurements were seen using 6 MV mode over 6 FFF. This difference in $\boldsymbol{D/D_{Rx}}$ is most apparent at the fetus, where differences between 6 MV and 6 FFF also had increased field size dependence. Smaller field sizes showed a decreased $\boldsymbol{D/D_{Rx}}$ with the 6 FFF 2.8x2.8 cm^2 field having a 185% lower dose compared to 6 MV (**Figure 3**). It is important to note that large FFF field sizes would not be used clinically (at present), but are included in this study for comparison.

Photon therapy data can be compared to Task Group 158[26] in which they measured OOF $\boldsymbol{D/D_{Rx}}$ for 6 MV photon fields. Task Group 158 references data collected by Mutic et al.[30] on a 6 MV Elekta Precise using a 20x40x120 cm^3 water-equivalent plastic phantom and 10x10 cm^2 field size most closely mirrors our setup on the Elekta Versa HD. For our 10.3x10.3 cm^2 field the 6 MV Elekta Versa HD measurements agreed within 1 cGy/Gy at the thyroid, esophagus, and fetus. This is good agreement considering that our measurement depth varied substantially with anatomy.

Patients that are dependent on pacemakers are routinely treated with photon therapy and require OOF dosimetric evaluation. It is commonly established that the maximum allowable dose to a pacemakers is around 2 Gy.[2] Surface measurements performed by Starkschall et al. using a 6 MV Siemens Mevatron VI for 10x10 cm^2 fields can be compared to the 6 MV 10.3x10.3 cm^2 pacemaker measurements measured on the Varian Novalis Tx and Elekta Versa HD.[31] Although the treatment machines are different, the OOF dose agreed within 2 cGy/Gy. This could be attributed to improved designs with a newer generation of linac, or differences in leakage and collimation shielding configuration.

OOF $\boldsymbol{D/D_{Rx}}$ data for PBS proton therapy gathered with the IC-30 from this study can be compared to that gathered by Stolarczyk et al. using PBS with a 10x10x10 cm^3 beam with a range of 20 cm and modulation width of 10 cm. Comparing our PBS 10.3x10.3x10 cm^3 beam we found that at the level of the thyroid the $\boldsymbol{D/D_{Rx}}$ was higher than the value measured by Stolarczyk.[32] This can be partially attributed to the difference in measurement depth and in detectors. We measured the thyroid to be at approximately 2 cm depth, significantly shallower than the 10 cm from Stolarczyk's study. Furthermore, this study warrants further investigation of the energy response of the IC-30 detector for high energy neutrons above 50.5 MeV. Nonetheless, our data did show similar trends to that reported in literature, most notably that in PBS an increase in the field size leads to a more substantial OOF $\boldsymbol{D/D_{Rx}}$. Pacemaker data was reported and can be used in future investigations, although it is very unlikely that a patient dependent on a pacemaker would be treated with proton therapy (due to device upset concerns from neutrons).[2]

Neutron therapy is a unique treatment modality. Because of the limited number of treatment facilities there has not been extensive research on the OOF $\boldsymbol{D/D_{Rx}}$ associated with patient treatment. We observed that by shrinking the field size there was an increase in OOF $\boldsymbol{D/D_{Rx}}$. We hypothesize that the increased collimation material in the beam leads to an increase in neutron capture which results in a higher OOF $\boldsymbol{D/D_{Rx}}$. Risler and Popescu recorded OOF in air measurements using a water tank setup positioned under the gantry.[20] For similar field sizes, detectors, and distances from the field edge our measurements were within the same order of magnitude, being on average slightly lower. This difference can be attributed to our data being measured at depth in a phantom, as opposed to in air.

Limitations of this study should be thoroughly evaluated for future comparisons. All beams were delivered using open square fields, whereas most modern treatments utilize multiple beam angles. No radiobiological effectiveness factors were associated with the measurements taken and could substantially alter comparisons between modalities. Additionally, this phantom did not contain the heterogeneities of an actual human such as lungs and bones. Creation of these structures were not feasible during the point of construction but are currently under investigation for future phantoms. Improved printer design could facilitate increased printing speed and the ability to print with materials of similar properties to that of tissues and bones. Care must be taken when filling the phantom with water as there is the possibility for air pockets to occur if anatomical features are situated above the fill port. Lastly, the phantoms head was secured with a PVC fitting, creating a gap between the head and torso. This gap was wrapped with 2 cm of bolus for measurements but still deviates from realistic anatomy. This study highlights the applicability of using 3D printing in the field of medical physics. The phantom was based on a real patient and therefore demonstrated improvement over generic anthropomorphic phantoms.

Conclusion:

In conclusion, we showed that the use of a 3D printed patient specific anthropomorphic phantom was valid for out-of-field dosimetry in photon, proton, and neutron therapies. Comparing absorbed dose between treatment modalities, proton therapy stood out as having the lowest out-of-field absorbed dose. This study will be useful for the confirmation of patient specific analytical and Monte Carlo models in the future. Further iterations of this concept can be applied to patients possessing unique anatomical features that could result in unknown out-of-field dose contributions. A unique aspect of this study is the lack of specialized fabrication tools required to construct the phantom. With an advanced 3D printer it is possible to create a phantom such as this for use in the clinic.

Summary

This study showed that an anthropomorphic phantom could be 3D printed using patient specific parameters in a cost effective manner that would be capable of OOF dosimetric measurements for a variety of treatment modalities. Through its use it was shown that for intracranial fields, proton therapy contributed the lowest OOF dose when compared to photon and neutron therapies delivering similar fields.

Future studies are warranted for 3D printed phantoms that include heterogeneities and other anatomical structures that could potentially be seen in a patient. Evaluation of the necessity of these structures and their clinical importance for accurately modeling OOF dose also requires future investigation.

As a first iteration this was a success and will pave the way for more accurately quantifying OOF dose in future patients. This study is novel in showing that any clinic with 3D printing capabilities can manufacture phantoms conforming to their own specifications for use in difficult cases and highlights the capability of using a patient specific phantom.

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Appendices

Table 1: All measurement data collected for Photon, Proton, and Neutron therapies for 2.8x2.8, 5.3x5.3, 7.8x7.8, 10.3x10.3, and 12.8x12.8 cm²fields at the location of the Thyroid, Esophagus, Pacemaker, and Fetus.

			D/D$_{Rx}$ (cGy/Gy)				
Distance from Field Edge	**Detector Location**	**Field (cm²)**	**Varian 6 MV**	**Elekta 6 MV**	**Elekta 6 FFF**	**SCCA**	**CNTS**
71	Fetus	2.8x2.8	0.0026	0.0021	0.0007		0.6964
69.75	Fetus	5.3x5.3	0.0030	0.0023	0.0011		0.5551
68.5	Fetus	7.8x7.8	0.0035	0.0026	0.0016		0.4658
67.25	Fetus	10.3x10.3	0.0043	0.0032	0.0022		0.4268
66	Fetus	12.8x12.8	0.0055	0.0045	0.0030		0.3857
39.4	Esophagus	2.8x2.8	0.0088	0.0075	0.0046		0.7006
38.15	Esophagus	5.3x5.3	0.0186	0.0124	0.0094		0.5745
36.9	Esophagus	7.8x7.8	0.0293	0.0219	0.0174		0.5116
35.65	Esophagus	10.3x10.3	0.0428	0.0325	0.0245		0.4888
34.4	Esophagus	12.8x12.8	0.0660	0.0448	0.0347		0.4697
24.4	Pacemaker	2.8x2.8	0.0361	0.0414	0.0309		1.7617
23.15	Pacemaker	5.3x5.3	0.1164	0.0945	0.0855	0.0529	1.4974
21.9	Pacemaker	7.8x7.8	0.2170	0.1721	0.1550	0.1283	1.3598
20.65	Pacemaker	10.3x10.3	0.3511	0.2379	0.2073	0.1412	1.4201
19.4	Pacemaker	12.8x12.8	0.4910	0.3513	0.2934		1.4682
15.4	Thyroid	2.8x2.8	0.3893	0.4263	0.2984		2.1231
14.15	Thyroid	5.3x5.3	0.7600	0.5888	0.4570	0.0929	1.9274
12.9	Thyroid	7.8x7.8	1.1974	0.8982	0.7187	0.3670	1.9437
11.65	Thyroid	10.3x10.3	1.8966	1.3867	1.0770	0.5216	2.2865
10.4	Thyroid	12.8x12.8	2.8853	2.1497	1.5710		2.6622

Below are collected data converted to absolute dose and normalized to1 Gy being delivered to cranial fields of 2.8x2.8, 5.3x5.3, 7.8x7.8, 10.3x10.3, and 12.8x12.8 cm^2 fields at isocenter. The out-of-field treatment measurement locations are the thyroid, pacemaker, esophagus, and fetus.

Thyroid Graph

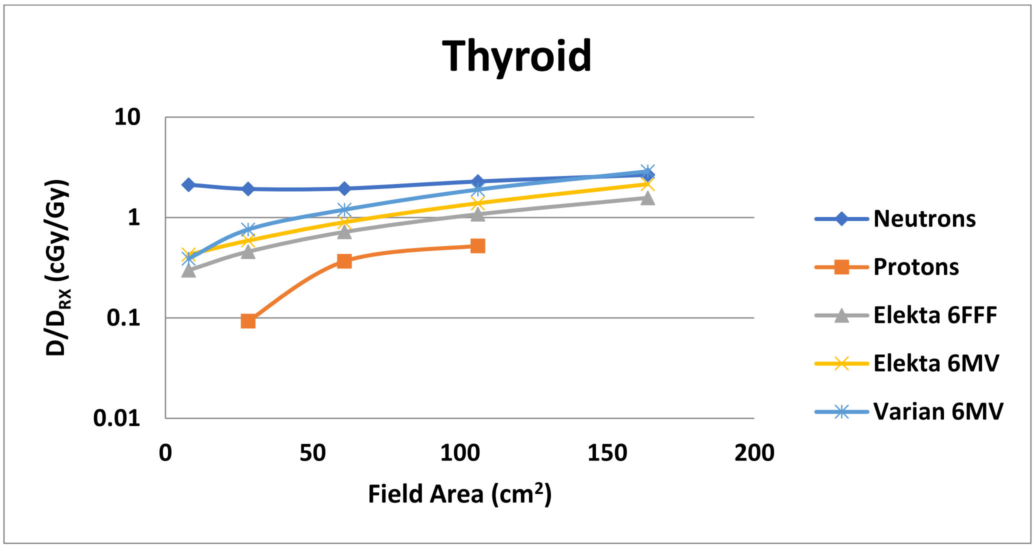


Figure 4: Thyroid; **D/D_{Rx}** *(cGy/Gy)vs. Field area in cm for Elekta Versa HD 6 MV (Yellow), Elekta Versa HD 6 FFF (Grey), Varian Novalis Tx (Blue), Proton therapy (Orange), and Neutron therapy (Blue)*

Pacemaker Graph

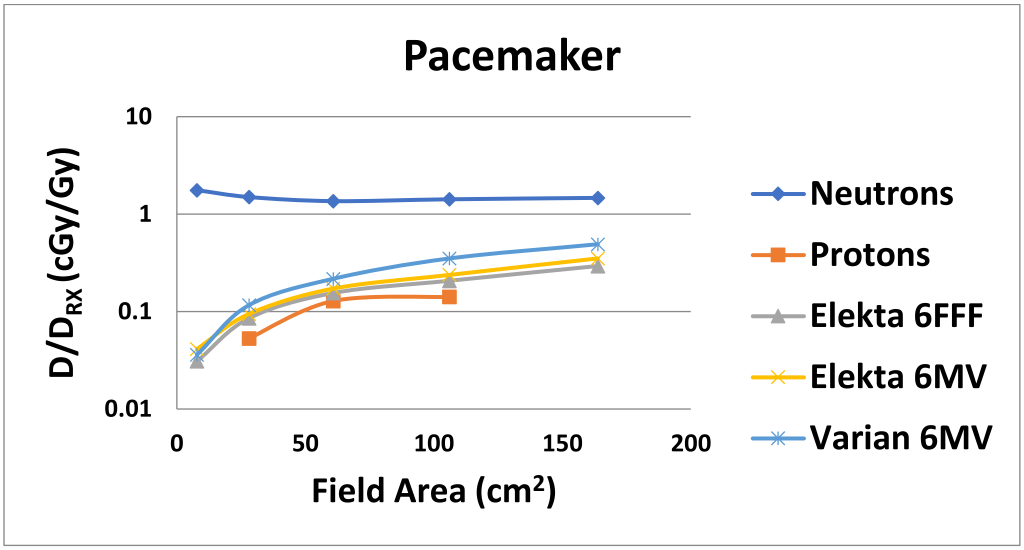


Figure 5: Pacemaker; **D/D$_{Rx}$** *(cGy/Gy) vs. Field area (cm) for Elekta Versa HD 6 MV (Yellow), Elekta Versa HD 6 FFF (Grey), Varian Novalis Tx (Blue), Proton therapy (Orange), and Neutron therapy (Blue)*

Esophagus Graph

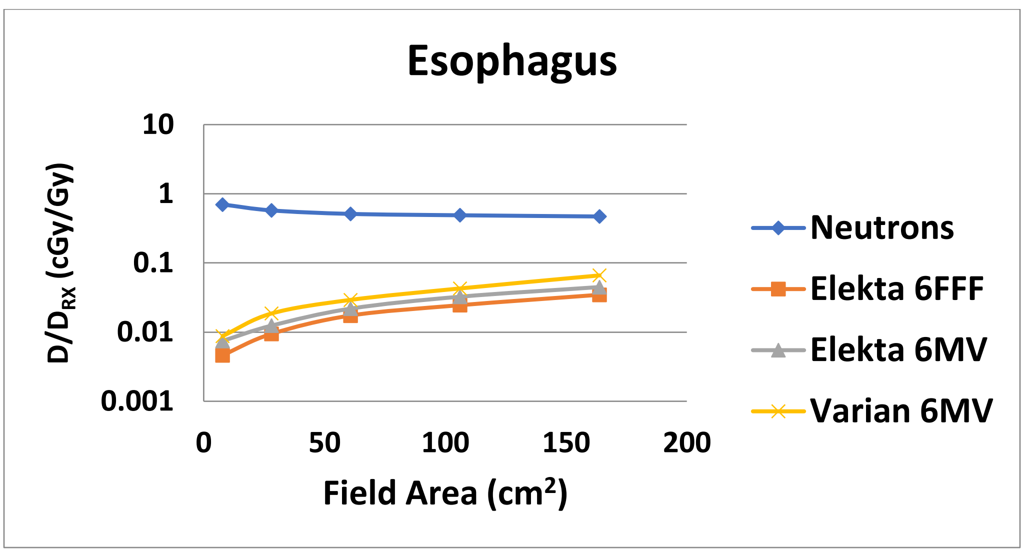


Figure 6: Esophagus; **D/D$_{Rx}$** *(cGy/Gy) vs. Field area in cm for Elekta Versa HD 6 MV (Orange), Elekta Versa HD 6 FFF (Grey), Varian Novalis Tx (Yellow) and Neutron therapy (Blue)*

Fetus Graph

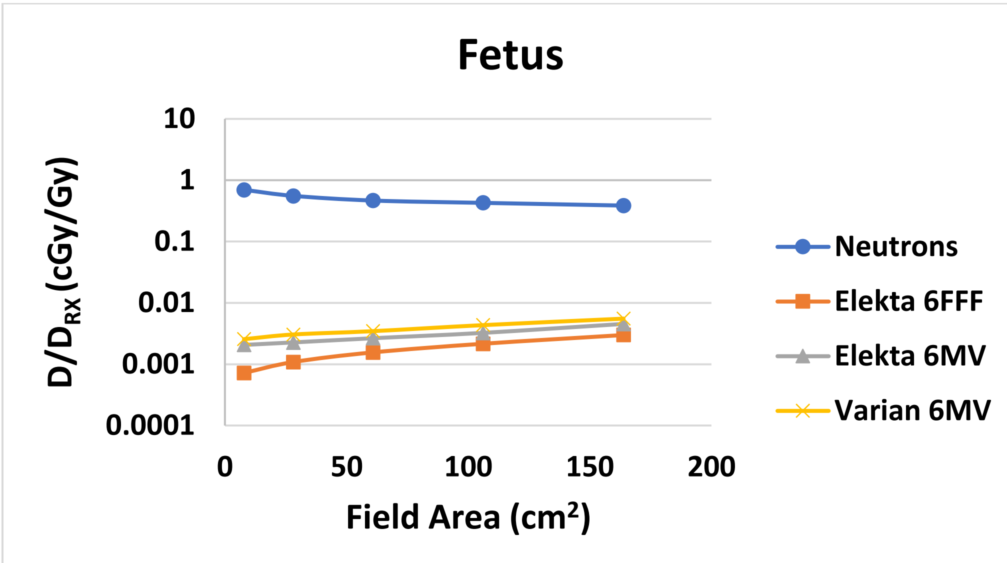


Figure 7: Fetus; **D/D_{Rx}** *(cGy/Gy) vs. Field area in cm for Elekta Versa HD (6 MV Orange), Elekta Versa HD 6 FFF (Grey), Varian Novalis Tx (Yellow) and Neutron therapy (Blue)*

Comparison to Mutic et al.

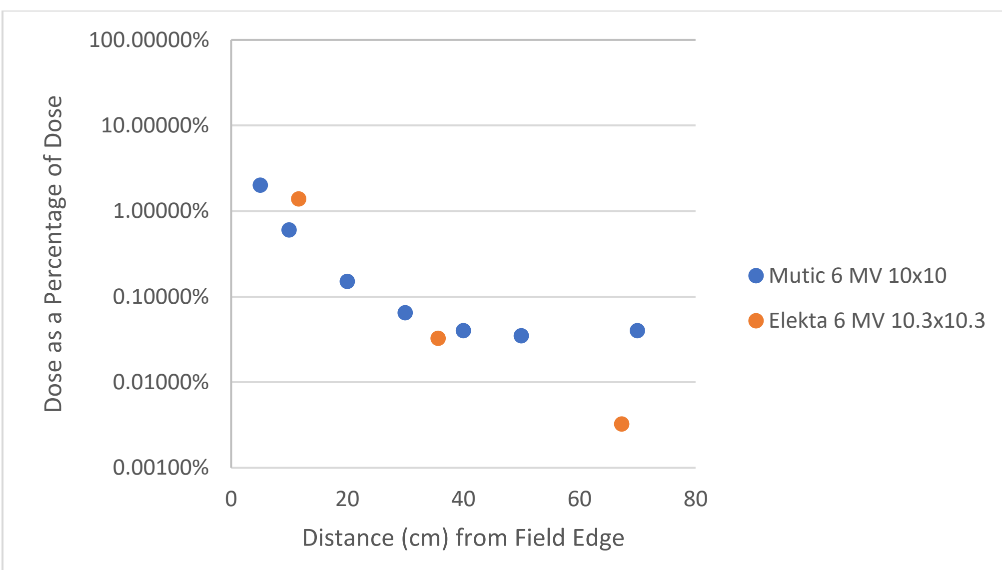


Figure 8: Comparison of data reported by Mutic et al.(Blue) for OOF dose from a 10x10 cm^2 field as a percentage of the d_{max} at the central axis on a 6 MV Elekta Precise compared to that taken collected using a 10.3x10.3 cm^2 field on a 6 MV Elekta Versa HD (Orange) in the locations of the thyroid, esophagus, and fetus.

SCCA treatment plans

5.3x5.3x10 cm^3

Seattle Cancer Care Alliance
Fred Hutch · Seattle Children's · UW Medicine
Proton Therapy Center

Patient name	Purple Ladie Marie	Report creation time	10 May 2019, 12:53:03 (hr:min:sec)
Patient ID	20181025	Plan last save time	27 Oct 2018, 16:28:18 (hr:min:sec)
Treatment plan name	5.3	Plan approved by	SPTC\phillip.taddei
Plan approved	Yes	Plan approval time	27 Oct 2018, 16:28:18 (hr:min:sec)

Plan Report

Beam Set overview

Beam Set name	5.3
Treatment technique	Pencil Beam Scanning
Treatment unit	FBTR1
Number of beams	1
Prescription	
Prescription	100 cGy x 1 fx = 100 cGy

Beam Data Overview

Beam #	Beam description	Gantry angle [deg]	Couch angle [deg]	# of Fractions	Treatment unit	Dose calculation algorithm
1	beam3	90.0	0.0	1	FBTR1	Pencil Beam, Version 4.1

Patient data

Patient ID	20181025
Patient name	Purple Ladie Marie
Patient gender	Female
Patient birth date	01 Jan 2018
Case data	
Case name	CASE 1
Physician	-
Body site	-

Treatment plan data

Treatment plan name	5.3
Plan last save time	27 Oct 2018, 16:28:18 (hr:min:sec)
Planned by	PJT
Number of beam sets	1
Patient treatment position	HFS : Head First Supine
Treatment plan approval data	
Approved by	SPTC\phillip.taddei
Plan comment	
Planning image set	
Name	CT 1
Modality	CT
Imaging system	120kVpSEAPBS13 31 Jul 2014, 09:57:46 (hr:min:sec)
Patient scanning position	HFS
Series date and time	25 Oct 2018, 18:29:41 (hr:min:sec)
Acquisition date and time	25 Oct 2018, 18:30:14 (hr:min:sec)
External ROI	External

General data

Treatment planning system	RayStation 6 (6.1.1.2)
Report creation time	10 May 2019, 12:53:03 (hr:min:sec)
Patient coordinate system	IEC 61217

ROI properties

No density override

Beam Set overview

Beam Set name	5.3
Treatment technique	Pencil Beam Scanning
Treatment unit	FBTR1
Number of beams	1

RayStation 6 (6.1.1.2) 1 of 9

Warnings [5.3]

Warnings confirmed at report creation by: SPTC\phillip.taddei.

- The selected imaging system '120kVpSEAPBS13' is not consistent with the station name 'PROCT01' specified in the DICOM files for image set 'CT 1'.
- The prescription is not fulfilled.
  Prescription: 100 cGy x 1 fx = 100 cGy
  Dose at 95.00% volume
  ROI: 10.3base
  Computed dose: 14 cGy x 1 fx = 14 cGy
  Relates to beam set dose

Beam Set Report

Beam Set data

Beam Set name	5.3
Modality	Protons
Treatment technique	Pencil Beam Scanning
Treatment unit	FBTR1
Commission time	12 Sep 2018, 00:34:00 (hr:min:sec)
Number of beams	1
DICOM Plan UID	1.2.752.243.1.1.20181027162818774.5300.31337
Planning image set	CT 1
CT to density table	120kVpSEAPBS13 31 Jul 2014, 09:57:46 (hr:min:sec)
Dose calculation algorithm	Pencil Beam, Version 4.1
Density calculation algorithm version	2.0
ROI(s) with density override	
Beam set approval data	
Approved by	SPTC\phillip.taddei
Structure set UID	1.2.752.243.1.1.20181027161837495.4200.47457
Structure set approval data	
Approved by	SPTC\phillip.taddei

Beam Data Overview [Right-Left: 2.23 Inf-Sup: 0.25 Post-Ant: -2.62]

#	Beam name (Description)	Number of energy layers	Gantry angle [deg]	Couch angle [deg]	Spot Tune ID	Range shifter	Range modulator	Block	Beam meterset [MU/fx]
1	beam3 (be...	27	90.0	0.0	4.0	18RS-40	No	No	576.67

Objectives

Dose	Function	ROI	Description	Robust	Weight	Value
	Physical Composite Objective			No		5.0632E-5
Plan	Max DVH	5.3base	Max DVH 105 cGy to 1% volume	No	1	2.1242E-5
Plan	Min DVH	5.3base	Min DVH 98 cGy to 98% volume	No	1	2.9390E-5

Constraints

No constraints defined

Prescription

ROI	10.3base
Fulfillment	Not fulfilled (14 cGy)
Dose type	Relates to beam set dose

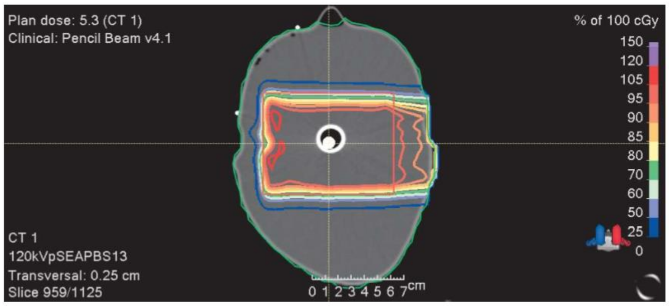
Patient setup

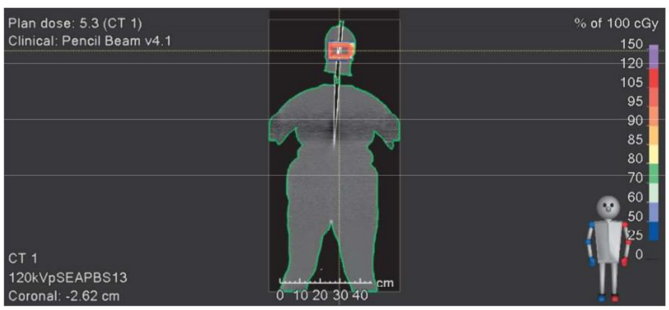
Localization point
No localization point defined.
Patient setup
No localization point defined.

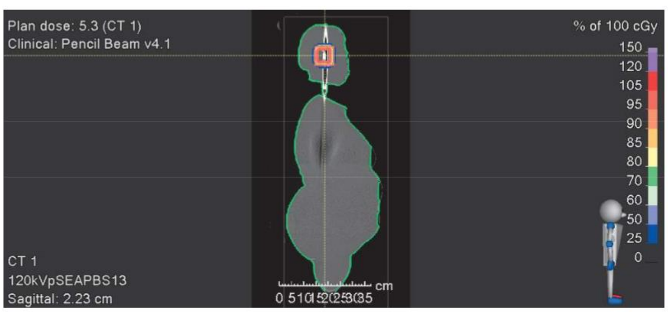
Seattle Cancer Care Alliance Fred Hutch · Seattle Children's · UW Medicine Proton Therapy Center	Patient name Patient ID Treatment plan name Plan approved	Purple Ladie Marie 20181025 5.3 Yes	Report creation time Plan last save time Plan approved by Plan approval time	10 May 2019, 12:53:03 (hr:min:sec) 27 Oct 2018, 16:28:18 (hr:min:sec) SPTC\phillip.taddei 27 Oct 2018, 16:28:18 (hr:min:sec)

Beamset dose data

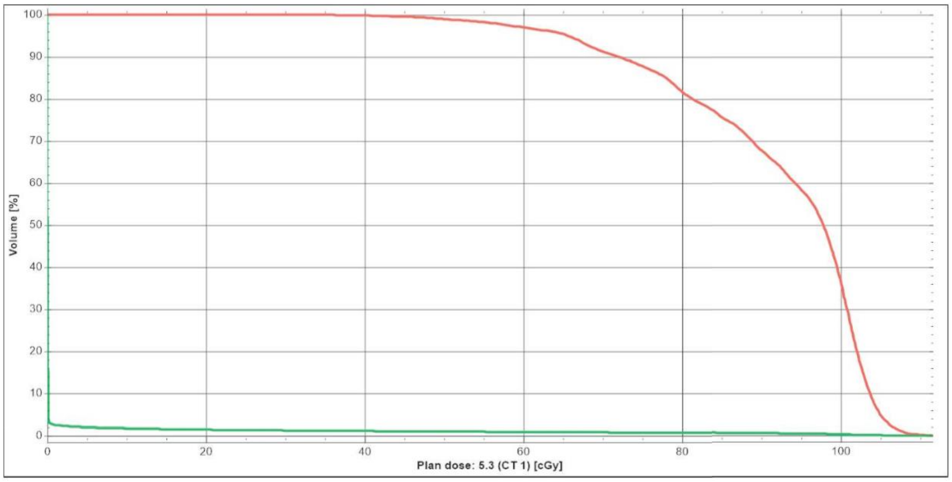
Isocenter name	5.3 1
Isocenter [cm]	Right-Left: 2.23 Inf-Sup: 0.25 Post-Ant: -2.62
Dose grid resolution [cm]	Right-Left: 0.30 Inf-Sup: 0.30 Post-Ant: 0.30
Beams	beam3







Patient name	Purple Ladie Marie	Report creation time	10 May 2019, 12:53:03 (hr:min:sec)
Patient ID	20181025	Plan last save time	27 Oct 2018, 16:28:18 (hr:min:sec)
Treatment plan name	5.3	Plan approved by	SPTC\phillip.taddei
Plan approved	Yes	Plan approval time	27 Oct 2018, 16:28:18 (hr:min:sec)



POI Dose statistics

Dose	POI	Dose [cGy]	Position Right-Left: [cm]	Inf-Sup: [cm]	Post-Ant: [cm]

Dose	Plan point	Dose [cGy]	Position Right-Left: [cm]	Inf-Sup: [cm]	Post-Ant: [cm]
Plan dose: 5.3 (CT 1)	DSP	101	2.23	0.25	-2.62

ROI Dose statistics [Beam Set dose]

Name	Volume [cm³]	D99 [cGy]	D98 [cGy]	D95 [cGy]	Average [cGy]	D50 [cGy]	D2 [cGy]	D1 [cGy]	% outside grid
10.3base	1061.10	6	9	14	68	77	106	107	0
5.3base	282.06	83	91	97	101	101	108	109	0
7.8base	608.24	50	56	66	92	98	107	108	0
External	87757.89	0	0	0	1	0	5	53	0

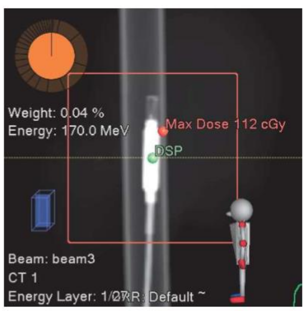
External — This ROI is set as the external ROI that defines the outer border of the patient

Beam data

Beam number	1
Beam name	beam3
Beam description	beam3
Gantry angle [deg]	90.0
Couch angle [deg]	0.0
Isocenter [cm]	5.3 1 - Right-Left: 2.23 Inf-Sup: 0.25 Post-Ant: -2.62
Treatment technique	Pencil Beam Scanning
Number of fractions	1
Beam weight [%]	100.0
Dose calculation algorithm	Pencil Beam, Version 4.1
Treatment unit	FBTR1
Commission time	12 Sep 2018, 00:34:00 (hr:min:sec)
SnoutID	18
Snout position [cm]	50.00
Spot Tune ID	4.0
Range shifter	18RS-40
Range modulator	No
Block	
No	
Number of energy layers	27
Number of spots	1417
Beam meterset [MU/fx]	576.67
Min spot weight [MU/fx]	0.0536
Max spot weight [MU/fx]	4.4247

Beam dose specification point

Coordinates [cm]	Isocenter
Dose per fraction [cGy]	100.7
Physical depth [cm]	7.94

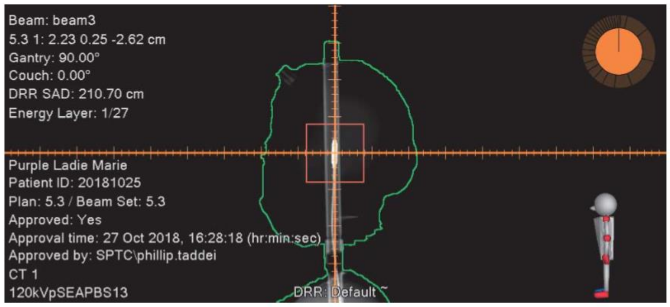


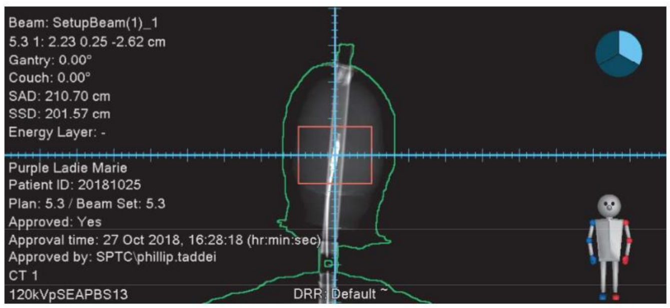
Energy Layers

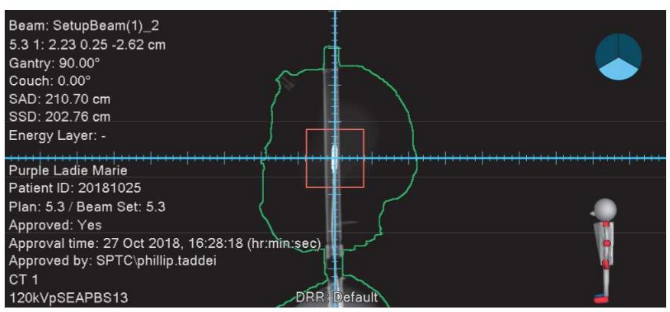
No	Energy [MeV]	Relative weight [%]	Number of spots	Spot spacing [cm]	Min spot weight [MU/fx]	Max spot weight [MU/fx]	No. of paintings
1	170.00	0.04	1	1.72	0.2253	0.2253	1
2	166.80	0.79	2	1.54	0.1246	4.4247	1
3	163.60	2.90	21	1.23	0.0713	3.0243	1
4	160.40	10.50	50	1.09	0.0536	2.7582	1
5	157.10	15.25	71	1.03	0.1240	2.4273	1
6	153.80	14.69	76	1.04	0.1396	2.6151	1
7	150.60	7.76	70	1.05	0.0862	2.1122	1
8	147.40	5.47	68	1.06	0.0907	2.1830	1
9	144.30	4.57	67	1.07	0.0805	1.0503	1
10	141.20	4.06	67	1.08	0.0844	0.6330	1
11	138.20	3.66	67	1.09	0.1129	0.5292	1
12	135.30	3.28	67	1.11	0.1168	0.4852	1

13	132.50	3.00	67	1.12	0.1182	0.4146	1
14	129.70	3.17	65	1.14	0.1181	1.3801	1
15	126.90	2.36	60	1.15	0.1254	0.3326	1
16	124.10	2.19	60	1.17	0.1111	0.3019	1
17	121.40	2.19	60	1.18	0.1034	0.4942	1
18	118.70	1.76	55	1.20	0.0989	0.2776	1
19	116.10	1.76	55	1.23	0.0833	0.4197	1
20	113.60	1.67	52	1.25	0.0719	0.7478	1
21	111.10	1.47	51	1.27	0.0650	0.5285	1
22	108.60	1.35	50	1.29	0.0644	0.2584	1
23	106.10	1.44	50	1.32	0.0633	0.4864	1
24	103.60	1.31	46	1.34	0.0588	0.4344	1
25	101.20	1.23	42	1.37	0.0790	0.3931	1
26	98.80	1.15	40	1.40	0.0971	0.2942	1
27	98.50	0.96	37	1.41	0.1007	0.2649	1

Patient name	Purple Ladie Marie	Report creation time	10 May 2019, 12:53:03 (hr:min:sec)
Patient ID	20181025	Plan last save time	27 Oct 2018, 16:28:18 (hr:min:sec)
Treatment plan name	5.3	Plan approved by	SPTC\phillip.taddei
Plan approved	Yes	Plan approval time	27 Oct 2018, 16:28:18 (hr:min:sec)







Seattle Cancer Care Alliance
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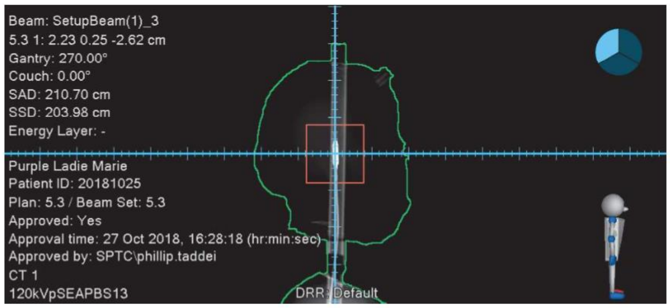
Patient name	Purple Ladie Marie	Report creation time	10 May 2019, 12:53:03 (hr:min:sec)
Patient ID	20181025	Plan last save time	27 Oct 2018, 16:28:18 (hr:min:sec)
Treatment plan name	5.3	Plan approved by	SPTC\phillip.taddei
Plan approved	Yes	Plan approval time	27 Oct 2018, 16:28:18 (hr:min:sec)



7.8x7.8x10 cm^3

Seattle Cancer Care Alliance
Fred Hutch · Seattle Children's · UW Medicine
Proton Therapy Center

Patient name	Purple Ladie Marie	Report creation time	10 May 2019, 12:54:13 (hr:min:sec)
Patient ID	20181025	Plan last save time	27 Oct 2018, 16:39:05 (hr:min:sec)
Treatment plan name	7.8	Plan approved by	SPTC\phillip.taddei
Plan approved	Yes	Plan approval time	27 Oct 2018, 16:39:05 (hr:min:sec)

Plan Report

Beam Set overview

Beam Set name	7.8
Treatment technique	Pencil Beam Scanning
Treatment unit	FBTR1
Number of beams	1
Prescription	
Prescription	100 cGy x 1 fx = 100 cGy

Beam Data Overview

Beam #	Beam description	Gantry angle [deg]	Couch angle [deg]	# of Fractions	Treatment unit	Dose calculation algorithm
1	beam2	90.0	0.0	1	FBTR1	Pencil Beam, Version 4.1

Patient data

Patient ID	20181025
Patient name	Purple Ladie Marie
Patient gender	Female
Patient birth date	01 Jan 2018
Case data	
Case name	CASE 1
Physician	-
Body site	-

Treatment plan data

Treatment plan name	7.8
Plan last save time	27 Oct 2018, 16:39:05 (hr:min:sec)
Planned by	PJT
Number of beam sets	1
Patient treatment position	HFS : Head First Supine
Treatment plan approval data	
Approved by	SPTC\phillip.taddei
Plan comment	
Planning image set	
Name	CT 1
Modality	CT
Imaging system	120kVpSEAPBS13 31 Jul 2014, 09:57:46 (hr:min:sec)
Patient scanning position	HFS
Series date and time	25 Oct 2018, 18:29:41 (hr:min:sec)
Acquisition date and time	25 Oct 2018, 18:30:14 (hr:min:sec)
External ROI	External

General data

Treatment planning system	RayStation 6 (6.1.1.2)
Report creation time	10 May 2019, 12:54:13 (hr:min:sec)
Patient coordinate system	IEC 61217

ROI properties

No density override

Beam Set overview

Beam Set name	7.8
Treatment technique	Pencil Beam Scanning
Treatment unit	FBTR1
Number of beams	1

Warnings [7.8]

Warnings confirmed at report creation by: SPTC\phillip.taddei.

- The selected imaging system '120kVpSEAPBS13' is not consistent with the station name 'PROCT01' specified in the DICOM files for image set 'CT 1'.
- The prescription is not fulfilled.
  Prescription: 100 cGy x 1 fx = 100 cGy
  Dose at 95.00% volume
  ROI: 10.3base
  Computed dose: 72 cGy x 1 fx = 72 cGy
  Relates to beam set dose

Beam Set Report

Beam Set data

Beam Set name	7.8
Modality	Protons
Treatment technique	Pencil Beam Scanning
Treatment unit	FBTR1
Commission time	12 Sep 2018, 00:34:00 (hr:min:sec)
Number of beams	1
DICOM Plan UID	1.2.752.243.1.1.20181027163905877.5900.86221
Planning image set	CT 1
CT to density table	120kVpSEAPBS13 31 Jul 2014, 09:57:46 (hr:min:sec)
Dose calculation algorithm	Pencil Beam, Version 4.1
Density calculation algorithm version	2.0
ROI(s) with density override	
Beam set approval data	
Approved by	SPTC\phillip.taddei
Structure set UID	1.2.752.243.1.1.20181027161837495.4200.47457
Structure set approval data	
Approved by	SPTC\phillip.taddei

Beam Data Overview [Right-Left: 2.23 Inf-Sup: 0.25 Post-Ant: -2.62]

#	Beam name (Description)	Number of energy layers	Gantry angle [deg]	Couch angle [deg]	Spot Tune ID	Range shifter	Range modulator	Block	Beam meterset [MU/fx]
1	beam2 (be...	26	90.0	0.0	4.0	18RS-40	No	No	1010.34

Objectives

Dose	Function	ROI	Description	Robust	Weight	Value
	Physical Composite Objective			No		4.8852E-5
Plan	Max DVH	7.8base	Max DVH 105 cGy to 1% volume	No	1	2.0036E-5
Plan	Min DVH	7.8base	Min DVH 98 cGy to 98% volume	No	1	2.8816E-5

Constraints

No constraints defined

Prescription

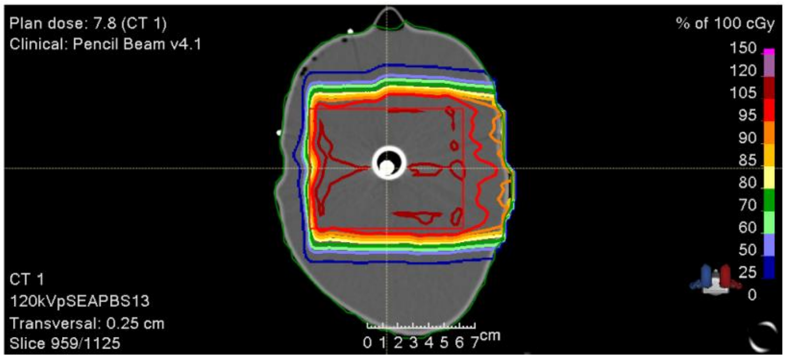
ROI	10.3base
Fulfillment	Not fulfilled (72 cGy)
Dose type	Relates to beam set dose

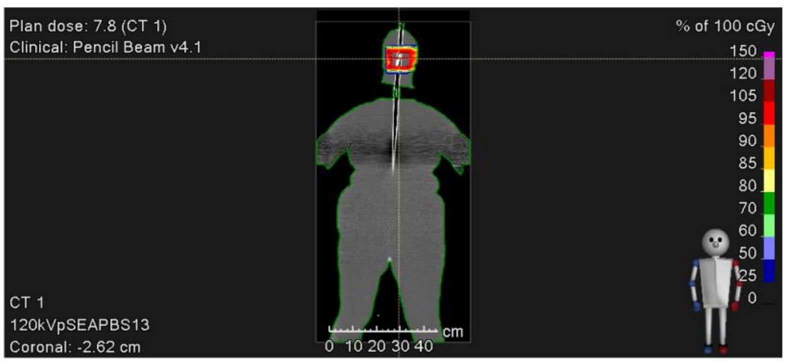
Patient setup

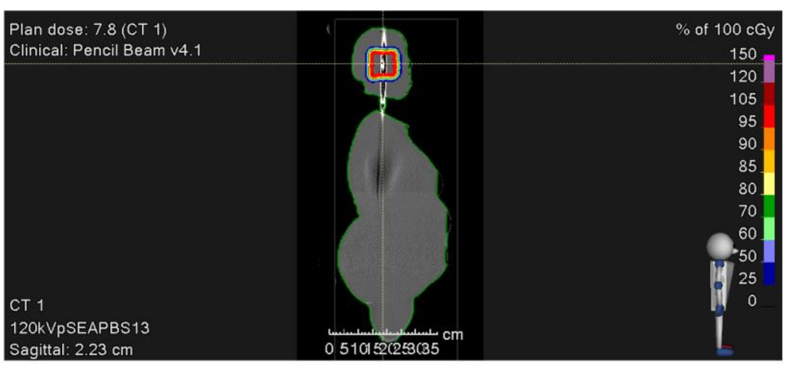
Localization point
    No localization point defined.
Patient setup
    No localization point defined.

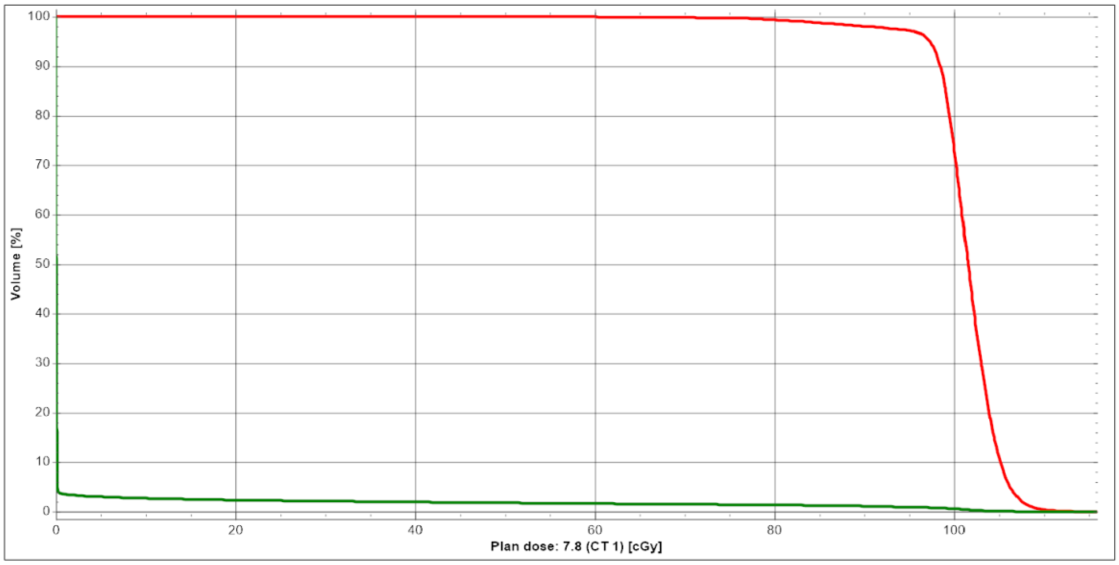
Beamset dose data

Isocenter name	7.8 1
Isocenter [cm]	Right-Left: 2.23 Inf-Sup: 0.25 Post-Ant: -2.62
Dose grid resolution [cm]	Right-Left: 0.30 Inf-Sup: 0.30 Post-Ant: 0.30
Beams	beam2









POI Dose statistics

Dose	POI	Dose [cGy]	Position Right-Left: [cm]	Inf-Sup: [cm]	Post-Ant: [cm]

Dose	Plan point	Dose [cGy]	Position Right-Left: [cm]	Inf-Sup: [cm]	Post-Ant: [cm]
Plan dose: 7.8 (CT 1)	DSP	105	2.23	0.25	-2.62

ROI Dose statistics [Beam Set dose]

Name	Volume [cm³]	D99 [cGy]	D98 [cGy]	D95 [cGy]	Average [cGy]	D50 [cGy]	D2 [cGy]	D1 [cGy]	% outside grid
10.3base	1061.10	59	66	72	95	100	107	108	0
5.3base	282.06	80	87	97	101	101	108	109	0
7.8base	608.24	83	90	97	101	102	108	109	0
External	87757.89	0	0	0	2	0	36	93	0

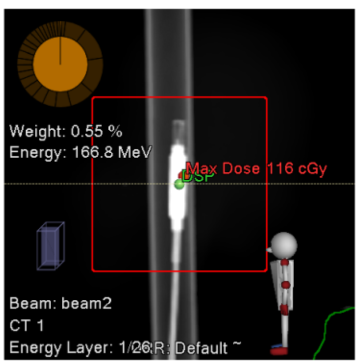
External — This ROI is set as the external ROI that defines the outer border of the patient

Beam data

Beam number	1
Beam name	beam2
Beam description	beam2
Gantry angle [deg]	90.0
Couch angle [deg]	0.0
Isocenter [cm]	7.8 1 - Right-Left: 2.23 Inf-Sup: 0.25 Post-Ant: -2.62
Treatment technique	Pencil Beam Scanning
Number of fractions	1
Beam weight [%]	100.0
Dose calculation algorithm	Pencil Beam, Version 4.1
Treatment unit	FBTR1
Commission time	12 Sep 2018, 00:34:00 (hr:min:sec)
SnoutID	18
Snout position [cm]	50.00
Spot Tune ID	4.0
Range shifter	18RS-40
Range modulator	No
Block	
No	
Number of energy layers	26
Number of spots	2366
Beam meterset [MU/fx]	1010.34
Min spot weight [MU/fx]	0.0648
Max spot weight [MU/fx]	5.6047

Beam dose specification point

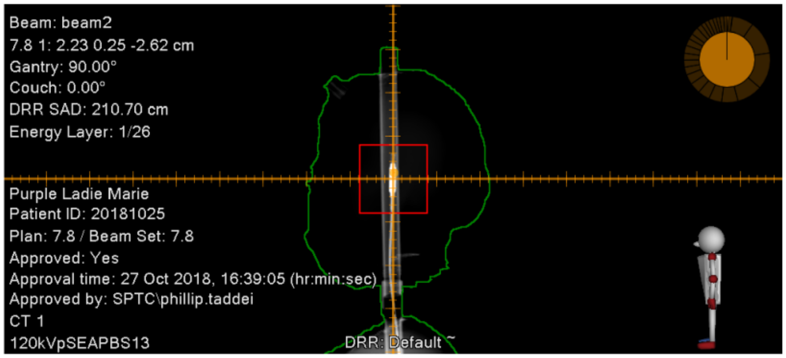
Coordinates [cm]	Isocenter
Dose per fraction [cGy]	104.7
Physical depth [cm]	7.94

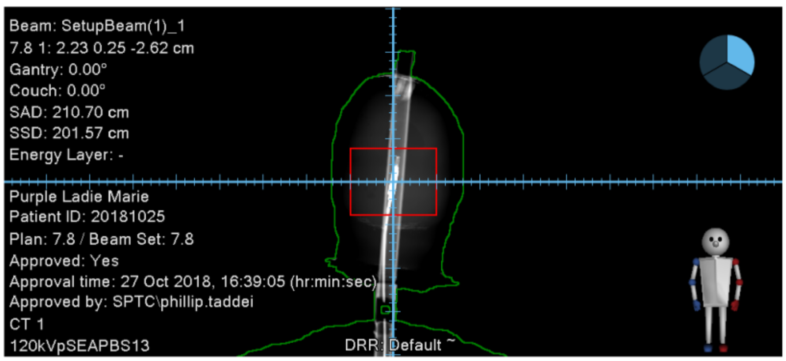


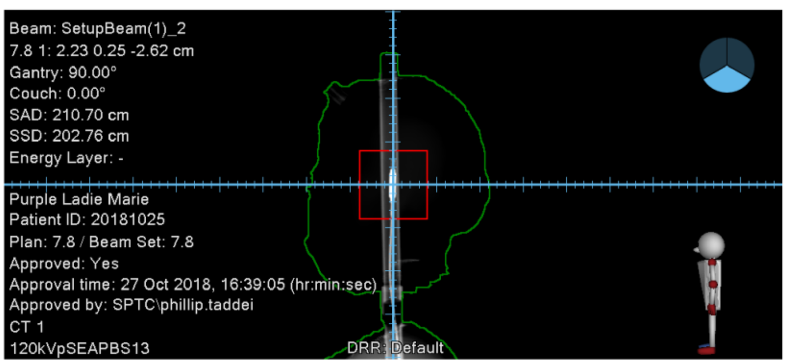
Energy Layers

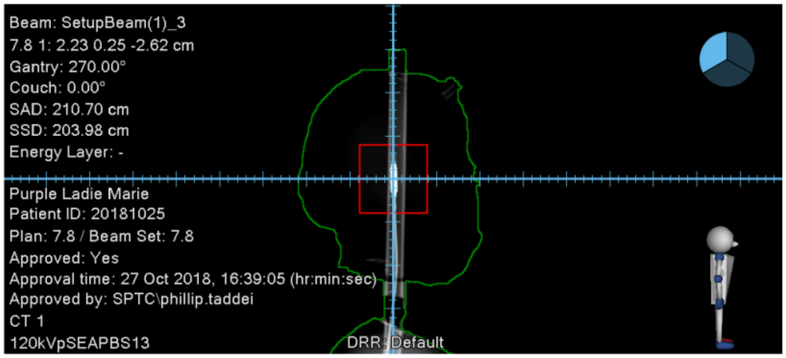
No	Energy [MeV]	Relative weight [%]	Number of spots	Spot spacing [cm]	Min spot weight [MU/fx]	Max spot weight [MU/fx]	No. of paintings
1	166.80	0.55	1	1.67	5.6047	5.6047	1
2	163.60	1.40	20	1.45	0.0847	4.4177	1
3	160.40	8.06	50	1.26	0.0701	3.5540	1
4	157.10	12.50	94	1.13	0.0870	2.8688	1
5	153.80	13.87	111	1.09	0.2313	2.8264	1
6	150.60	9.59	117	1.07	0.0653	2.5673	1
7	147.40	5.98	117	1.07	0.0720	2.3474	1
8	144.30	4.86	117	1.08	0.0804	1.2940	1
9	141.20	4.49	116	1.09	0.1431	0.8838	1
10	138.20	4.11	118	1.10	0.0662	0.7090	1
11	135.30	3.73	117	1.11	0.0648	0.6672	1
12	132.50	2.92	104	1.12	0.0723	0.6596	1

13	129.70	2.70	105	1.14	0.0812	0.8737	1
14	126.90	2.61	108	1.16	0.0756	2.6153	1
15	124.10	2.95	108	1.17	0.0813	2.6748	1
16	121.40	2.67	106	1.19	0.0738	2.7515	1
17	118.70	2.07	102	1.21	0.0725	0.9397	1
18	116.10	2.81	101	1.23	0.0795	2.9877	1
19	113.60	1.93	93	1.25	0.0850	1.6784	1
20	111.10	1.60	89	1.28	0.0848	0.5372	1
21	108.60	1.50	88	1.30	0.0882	0.4849	1
22	106.10	1.67	88	1.32	0.0874	0.8768	1
23	103.60	1.36	83	1.35	0.0988	0.4083	1
24	101.20	1.27	75	1.38	0.1072	0.3784	1
25	98.80	1.54	74	1.41	0.1138	0.5100	1
26	98.50	1.24	64	1.41	0.1143	0.3372	1


Beam: beam2
7.8 1: 2.23 0.25 -2.62 cm
Gantry: 90.00°
Couch: 0.00°
DRR SAD: 210.70 cm
Energy Layer: 1/26
Purple Ladie Marie
Patient ID: 20181025
Plan: 7.8 / Beam Set: 7.8
Approved: Yes
Approval time: 27 Oct 2018, 16:39:05 (hr:min:sec)
Approved by: SPTC\phillip.taddei
CT 1
120kVpSEAPBS13
DRR: Default


Beam: SetupBeam(1)_1
7.8 1: 2.23 0.25 -2.62 cm
Gantry: 0.00°
Couch: 0.00°
SAD: 210.70 cm
SSD: 201.57 cm
Energy Layer: -
Purple Ladie Marie
Patient ID: 20181025
Plan: 7.8 / Beam Set: 7.8
Approved: Yes
Approval time: 27 Oct 2018, 16:39:05 (hr:min:sec)
Approved by: SPTC\phillip.taddei
CT 1
120kVpSEAPBS13
DRR: Default


Beam: SetupBeam(1)_2
7.8 1: 2.23 0.25 -2.62 cm
Gantry: 90.00°
Couch: 0.00°
SAD: 210.70 cm
SSD: 202.76 cm
Energy Layer: -
Purple Ladie Marie
Patient ID: 20181025
Plan: 7.8 / Beam Set: 7.8
Approved: Yes
Approval time: 27 Oct 2018, 16:39:05 (hr:min:sec)
Approved by: SPTC\phillip.taddei
CT 1
120kVpSEAPBS13
DRR: Default


Beam: SetupBeam(1)_3
7.8 1: 2.23 0.25 -2.62 cm
Gantry: 270.00°
Couch: 0.00°
SAD: 210.70 cm
SSD: 203.98 cm
Energy Layer: -
Purple Ladie Marie
Patient ID: 20181025
Plan: 7.8 / Beam Set: 7.8
Approved: Yes
Approval time: 27 Oct 2018, 16:39:05 (hr:min:sec)
Approved by: SPTC\phillip.taddei
CT 1
120kVpSEAPBS13
DRR: Default

10.3x10.3x10 cm^3

Patient name	Purple Ladie Marie	Report creation time	10 May 2019, 12:54:40 (hr:min:sec)
Patient ID	20181025	Plan last save time	27 Oct 2018, 14:48:53 (hr:min:sec)
Treatment plan name	10.3	Plan approved by	SPTC\phillip.taddei
Plan approved	Yes	Plan approval time	27 Oct 2018, 14:48:53 (hr:min:sec)

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Plan Report

Beam Set overview

Beam Set name	10.3
Treatment technique	Pencil Beam Scanning
Treatment unit	FBTR1
Number of beams	1
Prescription	
Prescription	100 cGy x 1 fx = 100 cGy

Beam Data Overview

Beam #	Beam description	Gantry angle [deg]	Couch angle [deg]	# of Fractions	Treatment unit	Dose calculation algorithm
1	beam1	90.0	0.0	1	FBTR1	Pencil Beam, Version 4.1

Patient data

Patient ID	20181025
Patient name	Purple Ladie Marie
Patient gender	Female
Patient birth date	01 Jan 2018
Case data	
Case name	CASE 1
Physician	-
Body site	-

Treatment plan data

Treatment plan name	10.3
Plan last save time	27 Oct 2018, 14:48:53 (hr:min:sec)
Planned by	PJT
Number of beam sets	1
Patient treatment position	HFS : Head First Supine
Treatment plan approval data	
Approved by	SPTC\phillip.taddei
Plan comment	
Planning image set	
Name	CT 1
Modality	CT
Imaging system	120kVpSEAPBS13 31 Jul 2014, 09:57:46 (hr:min:sec)
Patient scanning position	HFS
Series date and time	25 Oct 2018, 18:29:41 (hr:min:sec)
Acquisition date and time	25 Oct 2018, 18:30:14 (hr:min:sec)
External ROI	External

General data

Treatment planning system	RayStation 6 (6.1.1.2)
Report creation time	10 May 2019, 12:54:40 (hr:min:sec)
Patient coordinate system	IEC 61217

ROI properties

No density override

Beam Set overview

Beam Set name	10.3
Treatment technique	Pencil Beam Scanning
Treatment unit	FBTR1
Number of beams	1

Warnings [10.3]

Warnings confirmed at report creation by: SPTC\phillip.taddei.

- The selected imaging system '120kVpSEAPBS13' is not consistent with the station name 'PROCT01' specified in the DICOM files for image set 'CT 1'.
- The prescription is not fulfilled.
  Prescription: 100 cGy x 1 fx = 100 cGy
  Dose at 95.00% volume
  ROI: 10.3base
  Computed dose: 97 cGy x 1 fx = 97 cGy
  Relates to beam set dose

Beam Set Report

Beam Set data

Beam Set name	10.3
Modality	Protons
Treatment technique	Pencil Beam Scanning
Treatment unit	FBTR1
Commission time	12 Sep 2018, 00:34:00 (hr:min:sec)
Number of beams	1
DICOM Plan UID	1.2.752.243.1.1.20181027144853701.2900.48514
Planning image set	CT 1
CT to density table	120kVpSEAPBS13 31 Jul 2014, 09:57:46 (hr:min:sec)
Dose calculation algorithm	Pencil Beam, Version 4.1
Density calculation algorithm version	2.0
ROI(s) with density override	
Beam set approval data	
Approved by	SPTC\phillip.taddei
Structure set UID	1.2.752.243.1.1.20181027144426567.2800.64574
Structure set approval data	
Approved by	SPTC\phillip.taddei

Beam Data Overview [Right-Left: 2.23 Inf-Sup: 0.25 Post-Ant: -2.62]

#	Beam name (Description)	Number of energy layers	Gantry angle [deg]	Couch angle [deg]	Spot Tune ID	Range shifter	Range modulator	Block	Beam meterset [MU/fx]
1	beam1 (be...	26	90.0	0.0	4.0	18RS-40	No	No	1422.60

Objectives

Dose	Function	ROI	Description	Robust	Weight	Value
	Physical Composite Objective			No		5.6387E-5
Plan	Max DVH	10.3base	Max DVH 105 cGy to 1% volume	No	1	2.0527E-5
Plan	Min DVH	10.3base	Min DVH 98 cGy to 98% volume	No	1	3.5859E-5

Constraints

No constraints defined

Prescription

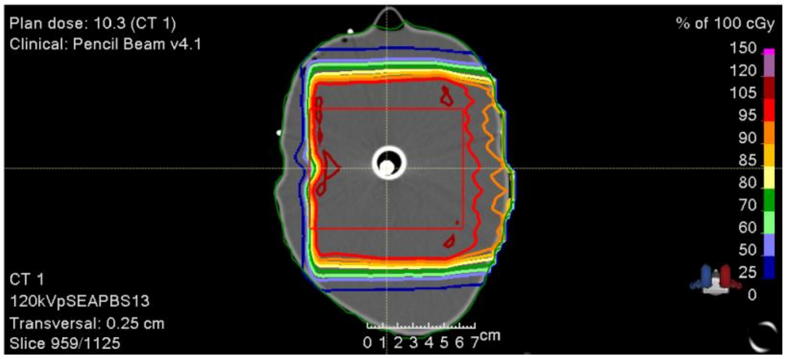
ROI	10.3base
Fulfillment	Not fulfilled (97 cGy)
Dose type	Relates to beam set dose

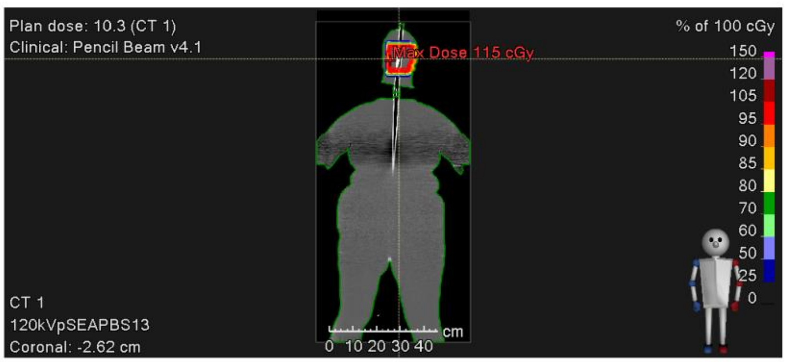
Patient setup

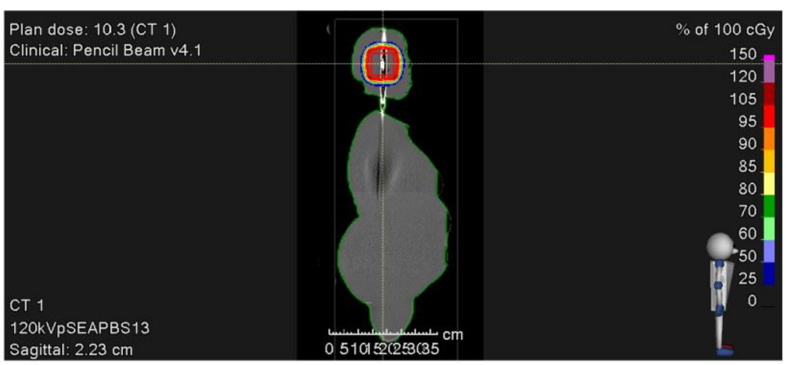
Localization point
No localization point defined.
Patient setup
No localization point defined.

Beamset dose data

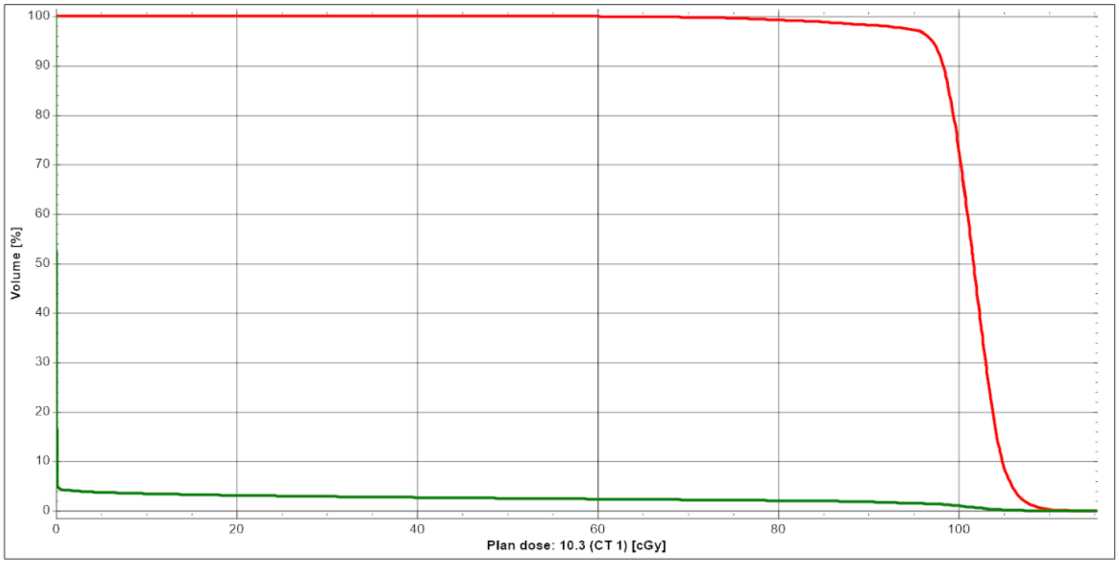
Isocenter name	10.3 1
Isocenter [cm]	Right-Left: 2.23 Inf-Sup: 0.25 Post-Ant: -2.62
Dose grid resolution [cm]	Right-Left: 0.30 Inf-Sup: 0.30 Post-Ant: 0.30
Beams	beam1







Seattle Cancer Care Alliance Fred Hutch · Seattle Children's · UW Medicine Proton Therapy Center	Patient name Patient ID Treatment plan name Plan approved	Purple Ladie Marie 20181025 10.3 Yes	Report creation time Plan last save time Plan approved by Plan approval time	10 May 2019, 12:54:40 (hr:min:sec) 27 Oct 2018, 14:48:53 (hr:min:sec) SPTC\phillip.taddei 27 Oct 2018, 14:48:53 (hr:min:sec)



POI Dose statistics

Dose	POI	Dose [cGy]	Position Right-Left: [cm]	Inf-Sup: [cm]	Post-Ant: [cm]

Dose	Plan point	Dose [cGy]	Position Right-Left: [cm]	Inf-Sup: [cm]	Post-Ant: [cm]
Plan dose: 10.3 (CT 1)	DSP	103	2.23	0.25	-2.62

ROI Dose statistics [Beam Set dose]

Name	Volume [cm³]	D99 [cGy]	D98 [cGy]	D95 [cGy]	Average [cGy]	D50 [cGy]	D2 [cGy]	D1 [cGy]	% outside grid
10.3base	1061.10	83	91	97	101	102	108	109	0
5.3base	282.06	77	88	97	102	102	108	109	0
7.8base	608.24	83	92	97	101	102	107	108	0
External	87757.89	0	0	0	3	0	82	100	0

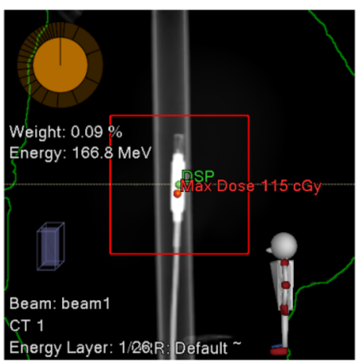
External — This ROI is set as the external ROI that defines the outer border of the patient

Beam data

Beam number	1
Beam name	beam1
Beam description	beam1
Gantry angle [deg]	90.0
Couch angle [deg]	0.0
Isocenter [cm]	10.3 1 - Right-Left: 2.23 Inf-Sup: 0.25 Post-Ant: -2.62
Treatment technique	Pencil Beam Scanning
Number of fractions	1
Beam weight [%]	100.0
Dose calculation algorithm	Pencil Beam, Version 4.1
Treatment unit	FBTR1
Commission time	12 Sep 2018, 00:34:00 (hr:min:sec)
SnoutID	18
Snout position [cm]	50.00
Spot Tune ID	4.0
Range shifter	18RS-40
Range modulator	No
Block	
No	
Number of energy layers	26
Number of spots	3125
Beam meterset [MU/fx]	1422.60
Min spot weight [MU/fx]	0.0649
Max spot weight [MU/fx]	4.9002

Beam dose specification point

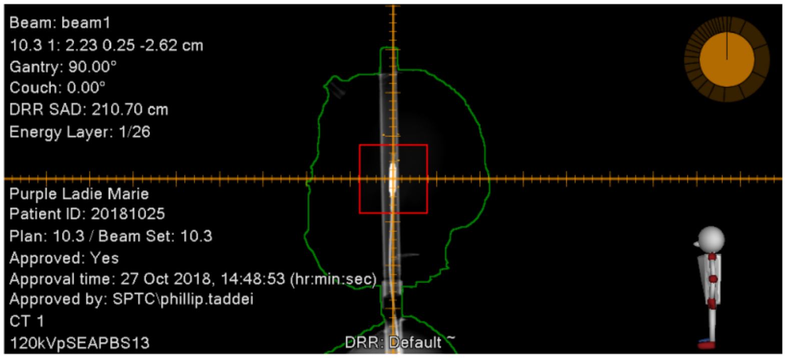
Coordinates [cm]	Isocenter
Dose per fraction [cGy]	102.9
Physical depth [cm]	7.94

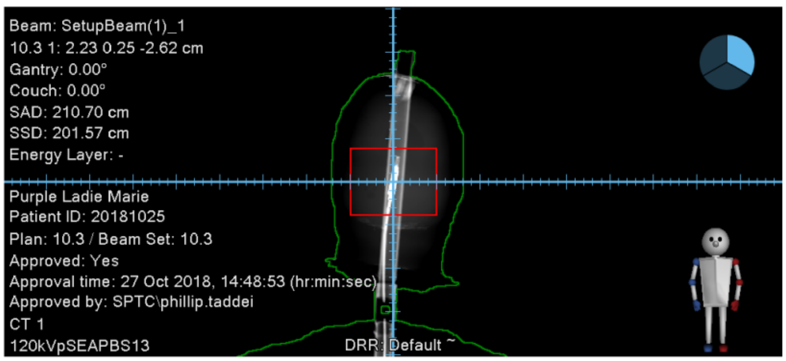


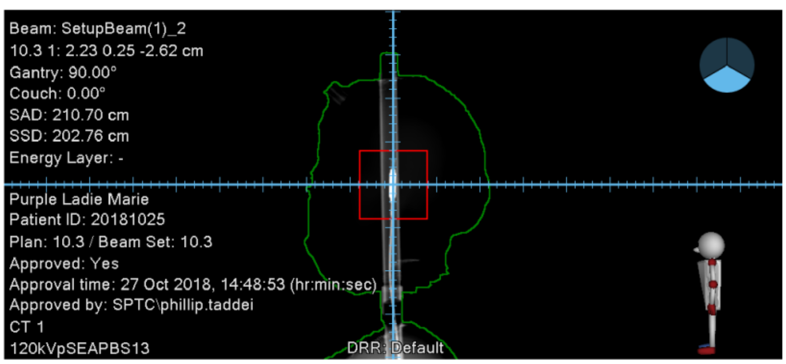
Energy Layers

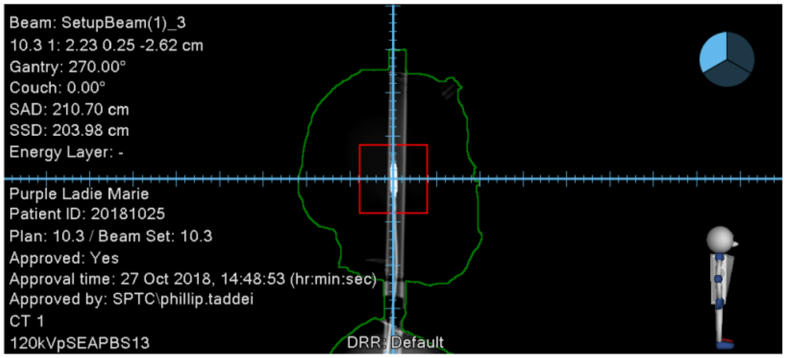
No	Energy [MeV]	Relative weight [%]	Number of spots	Spot spacing [cm]	Min spot weight [MU/fx]	Max spot weight [MU/fx]	No. of paintings
1	166.80	0.09	4	1.73	0.2389	0.4074	1
2	163.60	1.51	17	1.56	0.0904	4.9002	1
3	160.40	5.59	47	1.40	0.1274	4.0750	1
4	157.10	11.90	93	1.24	0.1115	4.3030	1
5	153.80	13.06	137	1.14	0.0738	3.2008	1
6	150.60	11.11	160	1.09	0.0649	3.2578	1
7	147.40	7.89	165	1.08	0.0922	3.1071	1
8	144.30	6.06	165	1.08	0.1325	3.3986	1
9	141.20	4.82	163	1.09	0.1092	1.5047	1
10	138.20	4.18	161	1.10	0.0892	1.7543	1
11	135.30	3.70	159	1.11	0.0881	1.4757	1
12	132.50	3.35	157	1.13	0.0826	1.4505	1

13	129.70	2.97	148	1.14	0.0685	1.4674	1
14	126.90	2.52	141	1.16	0.0704	0.8711	1
15	124.10	2.36	140	1.17	0.0732	1.0325	1
16	121.40	2.29	139	1.19	0.0790	0.9917	1
17	118.70	2.16	136	1.21	0.0848	0.8233	1
18	116.10	1.89	126	1.23	0.0813	0.7134	1
19	113.60	1.76	122	1.26	0.0892	0.7407	1
20	111.10	1.74	121	1.28	0.0982	0.7711	1
21	108.60	1.47	112	1.30	0.1018	0.4207	1
22	106.10	1.46	110	1.33	0.0995	0.5455	1
23	103.60	1.35	105	1.35	0.1018	0.6593	1
24	101.20	1.37	103	1.38	0.1054	0.4850	1
25	98.80	1.70	100	1.41	0.1218	0.6179	1
26	98.50	1.69	94	1.42	0.1300	0.6267	1


Beam: beam1
10.3 1: 2.23 0.25 -2.62 cm
Gantry: 90.00°
Couch: 0.00°
DRR SAD: 210.70 cm
Energy Layer: 1/26
Purple Ladie Marie
Patient ID: 20181025
Plan: 10.3 / Beam Set: 10.3
Approved: Yes
Approval time: 27 Oct 2018, 14:48:53 (hr:min:sec)
Approved by: SPTC\phillip.taddei
CT 1
120kVpSEAPBS13
DRR: Default


Beam: SetupBeam(1)_1
10.3 1: 2.23 0.25 -2.62 cm
Gantry: 0.00°
Couch: 0.00°
SAD: 210.70 cm
SSD: 201.57 cm
Energy Layer: -
Purple Ladie Marie
Patient ID: 20181025
Plan: 10.3 / Beam Set: 10.3
Approved: Yes
Approval time: 27 Oct 2018, 14:48:53 (hr:min:sec)
Approved by: SPTC\phillip.taddei
CT 1
120kVpSEAPBS13
DRR: Default


Beam: SetupBeam(1)_2
10.3 1: 2.23 0.25 -2.62 cm
Gantry: 90.00°
Couch: 0.00°
SAD: 210.70 cm
SSD: 202.76 cm
Energy Layer: -
Purple Ladie Marie
Patient ID: 20181025
Plan: 10.3 / Beam Set: 10.3
Approved: Yes
Approval time: 27 Oct 2018, 14:48:53 (hr:min:sec)
Approved by: SPTC\phillip.taddei
CT 1
120kVpSEAPBS13
DRR: Default


Beam: SetupBeam(1)_3
10.3 1: 2.23 0.25 -2.62 cm
Gantry: 270.00°
Couch: 0.00°
SAD: 210.70 cm
SSD: 203.98 cm
Energy Layer: -
Purple Ladie Marie
Patient ID: 20181025
Plan: 10.3 / Beam Set: 10.3
Approved: Yes
Approval time: 27 Oct 2018, 14:48:53 (hr:min:sec)
Approved by: SPTC\phillip.taddei
CT 1
120kVpSEAPBS13
DRR: Default

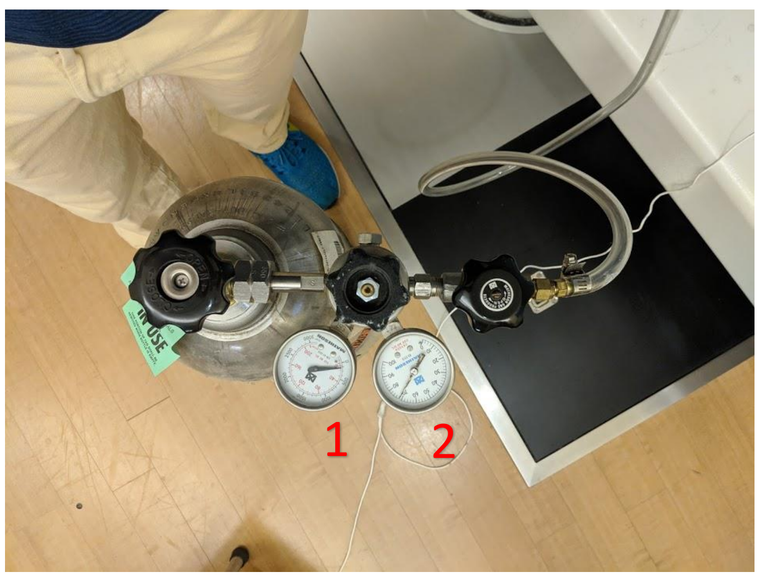
IC-17 Gas rate flow setup:

Setup:

1. Connect gas tank to first regulator (has reverse threading).
2. Second regulator should be attached through long clear tubing to first regulator.
3. Connect flow rate monitor though small surgical tubing and connector pin from second regulator.
4. Connect detector to output from flow rate monitor through small surgical tubing.
5. Connect detector bias.

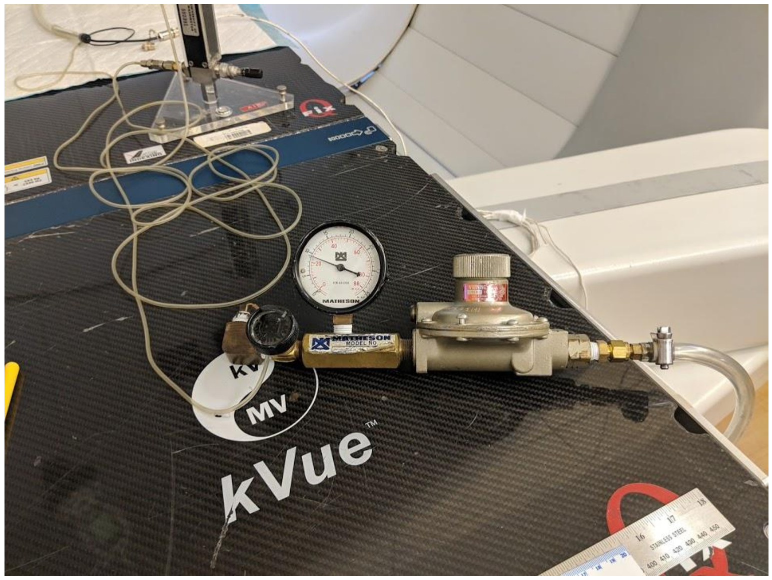
Turn on gas flow: (check valve pressure below)

Connect the TE gas tank to the first regulator:



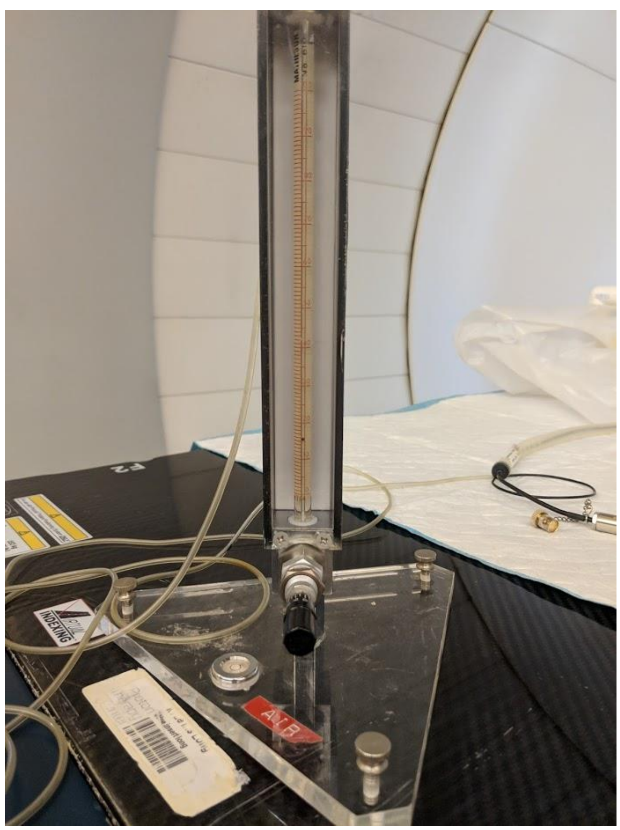
- When you turn on the gas flow:
    - Gauge **1** should have a pressure of *125*
    - Gauge **2** should have a pressure of *72*

Connect Regulator one to Regulator 2 through the long clear hose:



- When the gas flow is turned on:
  - Gauge on regulator 2 should show a pressure of: ***9.5***

Connect regulator 2 to the gas flow rate monitor tower:



Connect the flow rate monitor to the detector through the small surgical tubing:

- Flow rate monitor will probably have to be adjusted.
- The flow rate will bounce around a lot at first, but you want it to be stable at 15 for a good amount of time before you take your measurements.
- The bubble tends to get stuck sometimes, so give it time.

Comments:

- Don't adjust any of the nobs besides the main gas flow from the tank and bubble valve.
- Make sure to take pictures of everything (Setup, field size, electrometer, detector, etc.)
- The detector needs -300 for a bias (Don't turn on until gas has been flowing)
- The Tissue Equivalent gas is flammable
- Check gas flow by using a balloon/condom wrapped over the tubing