RAYSTATION DOSE CALCULATION ALGORITHMS

Depending on the modality, RayStation uses different beam models and dose calculation engines.* Some engines are used for calculation of dose with clinical accuracy while some are used during optimization of treatment plans. The patient model, i.e. voxelization and assignment of material properties in the patient volume, is the same for all modalities.

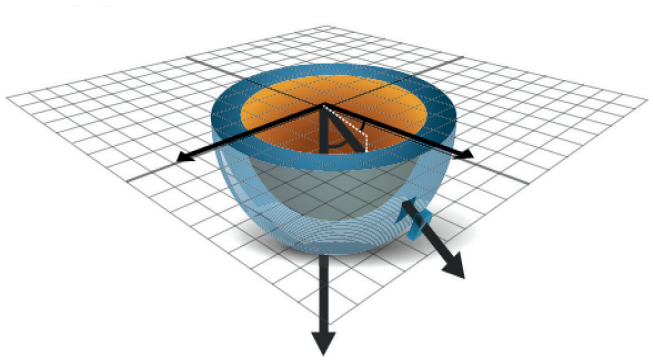
THE PATIENT MODEL

In preparation for a dose calculation, a patient model is created in the dose grid resolution. Typically, CT intensity values are mapped to mass densities through the CT calibration table. For CBCT the conversion to mass densities follows a step-wise function which results in bulk densities. When mass densities have been established, material properties are assigned according to what is likely to occur in a human body. From the material properties quantities relevant to the dose calculation are derived such as electron density and stopping power. It is also possible to assign material overrides which take precedence over the materials derived from the image data.

PHOTONS

The clinical dose engine for photons is called CC (Collapsed Cone). During optimization, a simplified dose engine called SVD (Singular Value Decomposition) is used. The two engines also use different fluence calculation engines.

Sphere point kernel discretization



The sphere point kernel *describes the energy distribution in a 3D spherical grid from a primary energy deposit. The figure shows a volume element in the spherical grid defined by its radia, azimuthal and polar interval. The origin of the spherical coordinate system is the interaction point. The photon enters the plot from above.*

* All clinical dose calculation engines are described in detail in the RayStation Reference Manual.

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Director of Clinical Physics
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"Since we started using RayStation for IMRT planning, not a single plan has ever failed IMRT QA. It was not the case with the planning systems we used before.

CC

This engine is based on the well-known principles of collapsed cone convolution superposition.[1]

1. Fluence is calculated according to a multi-source model. The primary source (representing photons created in the bremsstrahlung target) is a spatially elliptic Gaussian, and the secondary source (representing photons created in the flattening filter) is a circular Gaussian. There are also two sources for contaminating electrons. One has the same shape as the secondary photon source and the other is a circular Gaussian source which represents the electrons created in the air. The collimators are modeled in their physical position along the beam. All collimators are regarded as flat, but there are both position offsets and semi-transparent sections at the leaf tips and along the leaf sides which represent the effect of leaf tip curvature and of the tongue-and-groove design respectively.
2. Photons from all sources incident on the patient surface are transported through the patient using a divergent bundle of ray traces over a regular grid. The energy resulting from attenuation of the primary photons is scored in each voxel taking into account the material properties. The depth hardening and off-axis softening of the energy spectrum is handled by considering the water equivalent depth.
3. The energy resulting from the attenuation of primary photons is further spread out using pre-computed EGSnrc kernels combining all relevant physical processes. Along each direction, the energy deposition is scaled according to the local photon attenuation.
4. Electron contamination is computed using a pencil beam algorithm and added to the photon dose.

Jeremy Donaghue, *M.S.*
Chief Medical Physicist
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Through vigorous testing of the photon dose algorithm in RayStation we found excellent agreement to measured data across four linacs, three head configurations, and two vendors. All data was found to be well within the published guidelines.

Patricia Sansourekidou,
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Our commissioning results were within 2% at 2 mm, well within the industry standard. When I work on beam commissioning in RayStation I remember why we bought it. The results are so beautiful, it makes me happy to be a physicist.

SVD

This engine is based on separating the lateral and depth direction of a pencil beam distribution in water and thereby save memory and increase calculation speed. The underlying idea was first described by Bortfeld et al.[2]

1. Fluence is calculated in a relatively coarse grid corresponding to the leaf width perpendicular to the MLC leaf motion and 2.5 mm in the parallel direction. All collimation is regarded as occurring in the plane of the MLC.
2. Using the energy spectrum of the beam, a cylindrically symmetric pencil beam dose distribution (kernel) in water is generated. Regarding the distribution as a matrix, the singular value decomposition expresses it as a series of outer products summed with decreasing weight factors in which only a few terms are necessary for an accurate reconstruction. The vectors of the outer products represent the lateral and depth directions of the kernel.
3. For each term of the decomposed kernel, the fluence is convolved with the radial distribution corresponding to the lateral direction of the kernel. The radiological depth of each voxel is computed by ray tracing. The convolved fluence is projected through the voxels and weighted with the depth direction of the kernel. So in addition to the error introduced by using a depth scaled pencil beam kernel, an additional approximation is introduced by the fact that lateral transport occurs along surfaces of the same radiological depth, i.e. parallel to the skin rather than perpendicular to the beam.

PROTONS

The proton dose engine in RayStation is a so-called pencil beam dose algorithm, where the proton fluence is decomposed into a large number of closely spaced pencil-beams.[3,4] The dose contribution from each of these pencil-beams is calculated by performing a factorization of the dose to the lateral proton fluence Φ and the longitudinal, integrated depth dose IDD components.

The fluence description of a PBS spot or a US/DS energy layer is determined from the energy dependent beam model phase space parameters, which include: an effective energy spectrum, the spatial-angular distribution moments at iso-center, the virtual source axis distance (X and Y), and the dose monitor detector sensitivity. In addition, the thickness and effective weights of the range modulation steps of a US/DS SOBP are also included in the beam model.

The decomposition of the total proton fluence of an energy layer into a number of discrete pencil-beams is different for a PBS and a US/DS beam in RayStation. For PBS, each spot is discretized to a number of pencil-beams (sub-spots), which are not reused, or shared with other spots. For US/DS beams, where the intensities of each energy layer are uniform, the fluence plane is discretized using an orthogonal grid, with a pencil-beam originating from each pixel.

If a range shifter or range compensator is present, they will be treated as being part of the patient and the tracing of pencil-beams will then start at the entrance plane of these devices instead of the patient outline. The effect of the block is included by calculating the transparency of each fluence pixel, which means that the block is modeled as being infinitely thin with an infinitely high density.

In the dose computation the phase space parameters are transported through the patient along the central axis of each pencil-beam. Energy loss of the mean beam energy is computed using the well-established Bethe-Bloch stopping expression,[5] while

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"The Provision Center for Proton Therapy was the first proton therapy center to treat patients using the RayStation treatment planning system. The data required by the RayStation pencil beam dose calculation algorithm was measured during three 8 hour beam shifts and was sent to RaySearch to prepare the beam data model for our system. The RayStation system modeled the data near perfectly. We are very happy with the data modeling and the exceptionally good agreement between measured and calculated data for our uniform scanning beam delivery system.

the angular-spatial distribution is determined in the framework of Fermi and Eyges [6,7] with a modified multiple coulombs scattering of Rossi.[8] The IDD is obtained by scaling a water reference IDD, which is obtained from the energy spectrum of the beam model. Φ is determined by the spatial distribution moment, with an additional contribution from nuclear scattering, which is handled by a second Gaussian whose width and relative weight is a function of the initial beam energy and radiological depth of the pencil-beam.[4]

ELECTRONS

The dose calculation method for electron beams is Monte Carlo (MC). It is implemented by a beam phase space model and an in-patient energy transport and energy scoring part. Dose can be calculated for beams collimated by applicators w/o patient specific cutouts and bolus.

1. Direct electrons are sampled from parameterized effective energy and spatial-angular distributions. The energy spectrum is determined from a measured open field depth dose such as to capture the characteristics of direct electrons specifically. The spatial-angular part is described by an expression that accounts for the elements of a dual scattering foil beam line: a primary foil, a primary collimator cone and a secondary scattering foil with radially varying thickness. The direct electrons are transported by MC through a linac specific model of the treatment head geometry to the patient surface. The geometry is represented by a stack of geometry objects to model jaws, multi-leaf collimator, applicator scraper layers and an optional cutout. Multiple scattering in air is modelled according to the Goudsmit-Saunderson theory and random hinge transport steps [9]. A direct electron that hits the surface of a collimator element is stopped but may generate an indirect electron by out-scatter (see below).
2. When a direct electron hits e.g. a scraper layer a dedicated edge scatter MC transport code simulates a continued transport in the collimator material accounting for energy loss, bremsstrahlung and multiple scattering. Depending on a set of transport thresholds, the electron is either trapped inside the collimator or it is emitted back into the air column for further transport towards the patient giving rise to a 1–10% dose contribution.

The photon contamination dose component, mainly arising from bremsstrahlung in the scattering foils, is of the order of 1–15% depending on beam energy and treatment head design. The corresponding dose is calculated by the SVD dose engine and is added to the electron dose. A simplified energy fluence model is used where the energy spectrum is deduced from depth dose curves according to.[10] Laterally a rotational symmetric Gaussian distribution is applied with attenuation to account for the cutout aperture and the geometry of the most downstream scraper layer.

Dose calculation: RayStation uses the VMC++ [11] code for the in-patient dose calculation. The VMC++ code is optimized for three-dimensional dose calculations in voxel-geometries. The code solves the coupled photon/electron/positron transport problem and is thus capable of calculating dose distributions for electron beams as well as for photon beams. The algorithm uses a Class II condensed history (CH) scheme for the simulation of charged particle transport. Hence, bremsstrahlung interactions that result in the creation of photons above an energy threshold, and inelastic scattering that sets in motion secondary electrons with energy above a threshold, is treated discretely by creation and transport. Sub-threshold inelastic processes are accounted for using the Continuous Slowing Down Approximation (CSDA). For further details the reader is referred to [11] and references therein. The VMC++ code is setup to score dose to water.

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Electron Monte Carlo offers anatomically based treatment planning which accurately accounts for in-patient inhomogeneities with fast dose computation times. The ability to combine and visualise eMC dose distributions with photon-based external beam techniques will facilitate improved plan optimisation in combined therapies and boost techniques.

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RayStation dose calculation algorithms Version: 2017-04-20

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