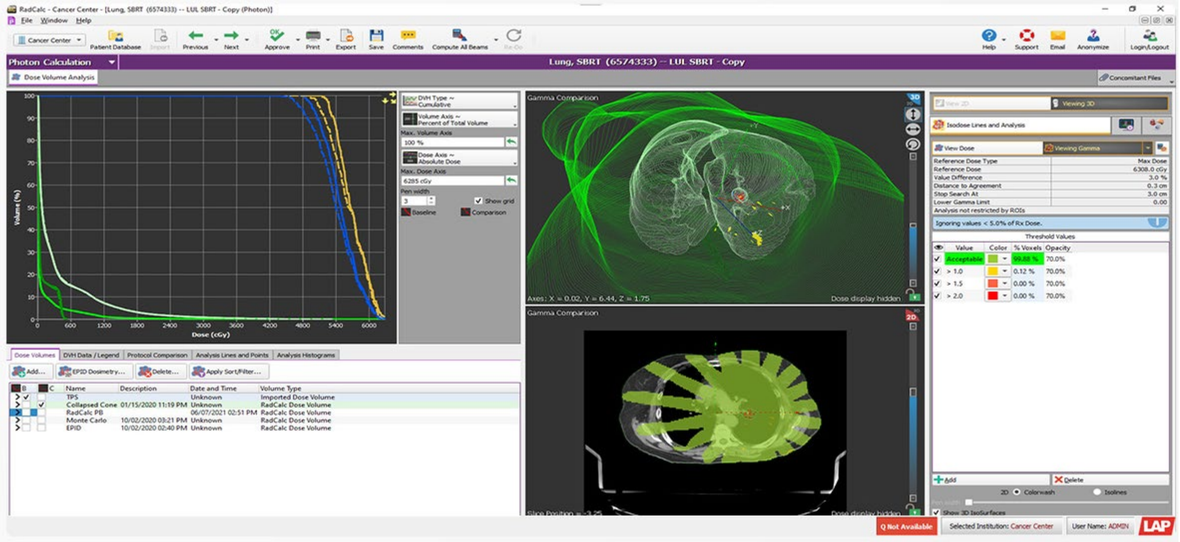
RadCalc’s 3D Monte Carlo and 3D Collapse Cone algorithms

This whitepaper explores RadCalc’s 3D dose algorithms. The 3D Collapsed Cone module was first introduced in version 7.0 released in beta in Aug of 2019, with clinical release in November. The 3D Monte Carlo module was released in version 7.1, with the beta release happening in September of 2019 and clinical release in January of 2020.

Extensive clinical evaluations were performed to validate RadCalc’s new 3D modules’ increasing the commitment to accuracy and reliability.

RadCalc’s 3D modules provides confidence and reliability for all field sizes in a single model with both the Collapsed Cone Superposition Convolution and BEAMnrc Monte Carlo.



RadCalc - Cancer Center - [Lung, SBRT (6574333) -- LUL SBRT - Copy (Photon)]

Lung, SBRT (6574333) -- LUL SBRT - Copy

DVH Type ~ Cumulative

Volume Axis ~ Percent of Total Volume

Max. Volume Axis: 100 %

Dose Axis ~ Absolute Dose

Max. Dose Axis: 6285 cGy

Pen width: 3

B	C	Name	Description	Date and Time	Volume Type
✓	☐	TPS		Unknown	Imported Dose Volume
☐	✓	Collapsed Cone	01/15/2020 11:19 PM	Unknown	RadCalc Dose Volume
☐	☐	RadCalc PB		06/07/2021 02:51 PM	RadCalc Dose Volume
☐	☐	Monte Carlo	10/02/2020 03:21 PM	Unknown	RadCalc Dose Volume
☐	☐	EPID	10/02/2020 02:40 PM	Unknown	RadCalc Dose Volume

Axes: X = 0.02, Y = 6.44, Z = 1.75

Dose display hidden

Slice Position = -3.25

Dose display hidden

Reference Dose Type	Max Dose
Reference Dose	6308.0 cGy
Value Difference	3.0 %
Distance to Agreement	0.3 cm
Stop Search At	3.0 cm
Lower Gamma Limit	0.00

Analysis not restricted by ROIs

Ignoring values < 5.0% of Rx Dose.

Threshold Values

👁	Value	Color	% Voxels	Opacity
✓	Acceptable	🟩	99.88 %	70.0%
✓	> 1.0	🟨	0.12 %	70.0%
✓	> 1.5	🟧	0.00 %	70.0%
✓	> 2.0	🟥	0.00 %	70.0%

2D ● Colorwash ○ Isolines

✓ Show 3D IsoSurfaces

Selected Institution: Cancer Center

User Name: ADMIN

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1.1 Introduction

Collapsed Cone Superposition algorithms have been the most commonly used in treatment planning systems for nearly a quarter century and are the most trusted model-based dose calculation algorithm.

> The Collapsed Cone dose computation process involves computing the incident fluence with a 1mm resolution. The computation is sped up by the use of poly-energetic dose kernels optimized at a depth of 10 cm from a weighted fit of monoenergetic PDD curves, along with a set of beam hardening factors to account for spectrum changes with depth. The TERMA is determined using the same 1mm resolution of the incident fluence. Electron contamination parameters are added into the calculation during the dose computation process. The energy deposited into a given location in the dose grid is determined by 256 or 160 collapsed cones, which is then summed to determine the final dose for each voxel within the volume.

Monte Carlo is widely considered to be the gold standard in terms of dose accuracy and our goal is to build confidence in the most uncertain planned doses.

> Modern day Monte Carlo methods benefit from more affordable computing power and powerful variance reduction techniques. These techniques are used to reduce calculation times. One such technique is directional bremsstrahlung splitting which involves only transporting photons that will contribute to the useful radiation field. The variance reduction methodologies employed by RadCalc minimize the time to compute dose without sacrificing accuracy. RadCalc's Monte Carlo algorithm offers benefits in the dose volume calculation for small heterogeneous cases, as well as highly modulated plans with large dose gradients where sparing normal healthy tissues can be more critical.

1.2 Key 3D Features in RadCalc

RadCalc enhances clinical practice by providing advanced tools for precise and efficient verification. Its seamless integration with treatment planning systems optimizes workflow efficiency, enabling clinicians to concentrate on patient care.

DVH Protocols

> Any number of DVH protocols can be defined from the analysis screen within RadCalc. Using rules in RadCalc, different DVH protocols can be automatically selected and applied to the specific plan. RadCalc automatically checks whether the DVH objectives are met for critical structures using both the TPS and RadCalc's 3D dose. Analysis reports are automatically attached to your verified plan and sent to your workstation via email or to a directory of your choice on your server.

3D Dose Analysis

> RadCalc provides Percent difference, DVH, Distance to Agreement, and Gamma analysis tools to evaluate 3D computations. The functionality includes RadCalcAIR (Automated Import & Reporting) providing a fully automated process for plan import, computation, 3D dose analysis and report generation. RadCalc's fully automated process immediately alerts you to plans that fail to pass your pre-set Gamma analysis acceptance

criteria. RadCalc allows automatically applying different Gamma calculation defaults and acceptance criteria based on user defined rules.

Auto Modeling

The RadCalc 3D modules utilize an automated beam commissioning process in conjunction with the users measured data to produce a customized beam model, the user only needs to press a button to generate the necessary models based upon their existing data.

The collapsed cone modeling process fully utilizes the existing measured data within RadCalc, therefore there are no new data requirements required from users.

The Monte Carlo modeling process partially uses the existing measured data within RadCalc. This data is used strictly as part of a simple matching process to identify the best matching RadCalc Monte Carlo machine file using a pre-computed set of PDD and Off Axis Profile data. Once this is determined, a reference dose calculation is performed in order to determine the reference dose conversion factor which converts the deposited energy to absorbed dose in the patient.

Standard beam geometries can easily be reviewed and analyzed within the same simple user interface during the commissioning process.

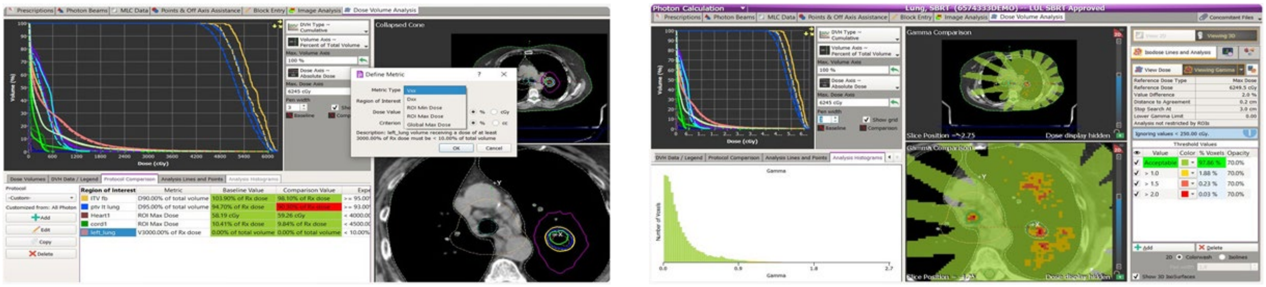

Image 1 RadCalc key 3D analysis features

1.3 Clinical Evaluation Evidence

As RadCalc has continuously evolved it has incorporated new recommendations from the American Association of Physicists in Medicine (AAPM) to enhance its accuracy and reliability. These include the recommendations of the AAPM TG-218 and TG-219[1,2].

Despite the evolving standards, the foundational criteria of achieving agreements within +/- 5.0% have remained a benchmark, ensuring consistency in its performance. The development team at RadCalc has always aimed to tighten these criteria as much as possible, striving for the highest levels of precision in dose verification[3]. This commitment to accuracy is reflected in the robust clinical evaluations and consistent performance improvements seen in RadCalc's subsequent versions.

By integrating these rigorous standards and adapting to new guidelines, RadCalc has solidified its reputation as a trusted and reliable tool in radiation therapy, ensuring that patients receive the safest and most effective treatments possible.

3D Collapsed Cone Module	**3D Monte Carlo Module**

1.3.1 3D Collapsed Cone Module

3D Collapsed Cone

The collapsed cone algorithm originates from the Dosimetry Check technology acquired from Math Resolutions, LLC and is now fully owned by LifeLine Software, Inc.

Support for CT images was added to RadCalc to convert a CT voxel from a Hounsfield Unit to density for 3D collapsed cone dose computations.

The fluence files used for the calculations are based on the fluence that has been utilized since the release of RadCalc version 4.0 in 2001. The dose algorithm involves a simple attenuation process of the primary radiation (i.e., the fluence) through the patient based on the density determined by the CT numbers. This process is similar to the existing ray traces used in the regions of interest module that has been available beginning with version 6.1. Collapsed cones, which are ray traces in 256 directions (160 starting in RadCalc version 7.3.2.0), cover the 3D space surrounding the dose point of interest and are used to determine the energy deposited to the dose point of interest from the various steps along each cone. A 3D dose matrix of points is used to define the entire area of the patient, allowing for a 3D dose distribution to be determined.

The validation testing was performed initially on an IMRT Thorax heterogeneous phantom from CIRS[4]. The purpose of the test was to verify the accuracy with which the algorithm can compute the dose to the lung by comparing the dose computed with the Collapsed Cone algorithm to a measured point.

A phantom with inhomogeneity inserts was used to create a curve of CT number to density in gm/cc. The density in the phantom water equivalent tissue material varied from 1.00 to 1.009 due to the beam hardening of the kVp energy x-ray used for CT scanning. In the lung area, the density was measured at 0.156, while in the bone area, it was 1.482. These values vary with position within the phantom but are noted to demonstrate the order of magnitude of the three density types. The phantom was irradiated with two different treatment plans: a four field “box” and a 460-degree arc, both using the same isocenter.

The four field “box” plan consisted of four radiation fields, 10x10 cm in size, anterior, posterior, right and left lateral, with 200 monitor units for each field.

The 360-degree arc plan consisted of a single full arc of a 10x10 cm field size with 200 monitor units total. The rotation computation was simulated for the CC computation with a beam every 10 degrees.

The phantom was irradiated on a Varian Medical Linear Accelerator (Varian, USA) at 6MV. The dose was measured with pinpoint ionization chamber from PTW, model 31006 (PTW –Freiburg, Germany) at the isocenter point in the left lung. The dose was also computed on the Varian Eclipse treatment planning system with two different algorithms, AAA and Acuros, for comparison purposes.

Four field box, dose cGy at isocenter:

Field	Meas (cGy)	RadCalc CC (cGy)	% Diff	AAA (cGy)	% Diff	Acuros (cGy)	% Diff
AP (0)	194	192.4	-0.80%	193.5	-0.30%	188.9	-2.70%
PA (180)	177	175.1	-1.10%	176	-0.60%	172.5	-2.60%
Left (90)	189.1	187	-1.10%	184.8	-2.30%	183.3	-3.20%
Right (270)	123.5	124.9	1.10%	113.9	-8.40%	120.8	-2.20%
Total	**683.6**	**679.4**	**-0.60%**	**668.2**	**-2.30%**	**665.5**	**-2.70%**

360 degree arc, dose cGy at isocenter:

Field	Meas (cGy)	RadCalc CC (cGy)	% Diff	AAA (cGy)	% Diff	Acuros (cGy)	% Diff
Arc	169	167	-1.20%	162.9	-3.70%	164.4	-2.80%

Table 1: The above data illustrate that in the most complicated treatment scenario for radiation oncology (dose in lung), the percent difference between the RadCalc collapsed cone algorithm and measurement was within +/-1.2% for all beams. In comparison, Varian's AAA algorithm was -2.3% off and Acuros was -2.7% off. For an arc plan, Varian's AAA was -3.7% off and Acuros was -2.8% off while RadCalc CC was -1.2% off.

The evaluation of these results from the collapsed cone calculations demonstrate that the standard phantom calculations were all within 2% of their expected value. Additionally, anonymized patient data freely provided from customers for testing purposes all demonstrated point dose comparisons within 2% and the Gamma Analysis Index for these plans were above 90%.

1.3.2 The 3D Monte Carlo Module

3D Monte Carlo

The Monte Carlo algorithm used to perform the 3D dose calculations comes in the form of off-the-shelf software, BEAMnrc (a.k.a. EGSnrc), and DOSExyz. These software programs were developed by the National Research Council of Canada and are widely considered the standard against which all dose calculation algorithms are compared. Although not developed by LifeLine Software, Inc., BEAMnrc and DOSExyz are utilized in the dose calculation process. They are used to transport particles through the machine components and then the patient.

The dose computation process is very straightforward. The CT dataset is first converted into a density and material matrix using a CT to-density table with air and water as the two materials. Aside from that, the beam parameters are written into the format needed by BEAMnrc and DOSExyz. These parameters are used to perform a Monte Carlo simulation, which produces a dose matrix with energy deposited into each voxel. This dose is then converted into RadCalc's internal format. The conversion process involves applying a reference dose conversion factor to the deposited energy, converting it into absorbed dose.

Over eighty patient calculations were performed, and the dose calculations were within acceptable ranges, with an average percent difference of 1% to 3% between the primary treatment planning system and the high passing Gamma Index values (i.e., 96% and above using 3% and 3mm as the criteria).

1.4 Additional 3DCC and 3DMC publications

RadCalc's exceptional accuracy provides confidence and reliability for all field sizes in a single model with both the Collapsed Cone Superposition Convolution and BEAMnrc Monte Carlo. Two papers are summarized here:

1: Evaluation of RadCalc 3DCC against Measured Data[5]

- **Focus**: Verification of RadCalc's 3D Calculation Module (3DCC) against clinical data.
- **Methodology**: Compared 3DCC dose calculations to measured data in various treatment plans, primarily using a water phantom.
- **Key Metrics**: Gamma pass rate, comparison between calculated and measured doses.
- **Results**: Showed a high level of agreement between RadCalc's 3DCC and measured data for most cases.
- **Main Findings**:
    - Gamma pass rates for 3%/3mm criteria ranged from 90-98%, depending on the complexity of the treatment plan.
    - Performance was slightly worse for highly modulated plans and cases with tissue inhomogeneities.

Summary:

The accuracy of the RadCalc 3D Collapsed Cone algorithm for all field sizes was validated directly with measurements for both simple and complex geometries, with and without heterogeneities, using international guidelines and published criteria such as TG 114 and TG 219. The modelling was performed with the user's custom beam data and with independent validation of the machine characteristics, including the Radiation Light Field Offset. The calculations were performed with both NVIDIA Tesla K20 and RTX 3080 GPUs, demonstrating RadCalc's hardware flexibility.

RadCalc's Collapsed Cone algorithm from version 7.1.4.1 was evaluated, as well as the changes implemented in version 7.2.2.0. The newest improvements in version 7.2.3.1 were not evaluated as part of this work. However, it is not surprising to see that even with version 7.2.2.0, the complex IMRT and VMAT deliveries met the recommendations of TG 219 with IMRT fields using a 2% and 2mm criteria and for the most complex nasopharynx VMAT plan meeting 3%/2mm criteria. Overall, for the modulated fields there was especially good agreement of less than 1mm DTA in the areas of steep dose gradients.

Open fields had PDD comparisons of less than 0.5% differences, and Off Axis Ratios (OAR) within 2% in the central 80%. Additionally, the researchers performed dose comparisons for heterogeneous phantoms, including a 2cm stepped phantom on top of the water surface for an enface and oblique beam geometry, as well as utilizing Lung, Bone, Air and Mediastinum geometries, of which the results were generally within 3.5% of the measured dose. These results are better than the 2.5% dose differences recommended for simple open or MLC shaped static fields in homogenous medium and the action limits that are recommended when doses exceed 5% difference for heterogeneous calculations.

2: Tuning and Validation of the New RadCalc 3DMC Based Pre-Treatment Verification Tool[6]

- **Focus**: Development and validation of RadCalc's Monte Carlo (3DMC) module for radiotherapy pre-treatment verification.
- **Methodology**: Dosimetric comparison between 3DMC and clinical measurements on phantom and patient data. Validation was performed on 70 VMAT plans.
- **Key Metrics**: Gamma pass rate, tuning of Additional Radiation to Light Field Offset (ARLF) parameter for dose accuracy.
- **Results**:
  - Gamma pass rates for 3%/3mm criteria were above 95% after tuning for all energy types.
  - Improved dose accuracy for complex cases, especially in lung cancer patients due to better handling of tissue inhomogeneity.
- **Main Findings**:
  - RadCalc 3DMC achieved higher accuracy compared to 3DCC, particularly for complex treatment sites.
  - The ARLF tuning significantly improved the agreement between 3DMC calculations and measured data.

Summary:

The results of RadCalc’s 3D Monte Carlo algorithm secondary check on the patient’s heterogeneous CT datasets were compared against on-couch homogeneous phantom measurements after fine tuning the models in RadCalc with a Gamma criteria of 2%/2mm and low dose thresholds of 50%. 70 VMAT plans were used for clinical validation of RadCalc’s 3D Monte Carlo algorithm for 6x, 10x, 6FFF and 10FFF against Eclipse v13.7 for both AAA and Acuros XB. Of the 70 plans, 20 were used for tuning and the other 50 were utilized as a validation set.

The RadCalc MC modeling process allows the user to choose the spot size and mean energy that best fits three open fields. Using this spot size and mean energy combination, a BEAMnrc-modeled machine is loaded, and every physical component is modeled. The unique auto-modeling method provides near-instantaneous beams with only one parameter that needs to be fine-tuned: the additional Radiation Light Field Offset (ARLF), also known as the Dosimetric Leaf Gap (DLG) in Varian terminology.

The authors quote their DLG for each energy and the resulting ARLF from the model tuning performed. The authors demonstrate the accuracy of RadCalc’s Monte Carlo against the Eclipse algorithms, and the on-couch homogenous phantom measurements against the Eclipse algorithms. As is the topic of the up-and-coming TG 360, the authors performed statistical methods on the comparison of the gamma passing rates. They utilized ROC curve analysis to set the acceptable plans for the on-couch measurements and the RadCalc Monte Carlo calculations as the 95th and 90th percentile, respectively. The confusion matrix, including the number of True Positives/Negatives and False Positives/Negatives, demonstrates Gamma Passing Rate comparisons against AAA/Acuros XB and a box chart that includes the on-couch measurements. In summary, these data show a high degree of agreement between the RadCalc MC and Acuros XB calculations, especially for the lung subset used.

As the authors conclude, after tuning, RadCalc's 3D Monte Carlo Algorithm provides a solution to independently verify treatment plans directly on the patient's CT with sensitivities and specificities similar to those of on-couch phantom solutions. It also detects inaccuracies in tissue inhomogeneities that homogeneous on-couch phantoms are unable to detect.

Aspect	**Paper 1: Evaluation of RadCalc 3DCC against Measured Data[4]**	**Paper 2: Tuning and Validation of the New RadCalc 3DMC Based Pre-Treatment Verification Tool[5]**
Module Type	3D Calculation (3DCC)	3D Monte Carlo (3DMC)
Verification Focus	Comparison of 3DCC with measured data	Validation of 3DMC using phantom and clinical plans
Methodology	Measured vs calculated doses (water phantom)	Tuning and validation using VMAT plans (phantom + patient)
Key Metric	Gamma pass rate	Gamma pass rate, ARLF tuning
Main Energy Types	6X, 10X	6X, 10X, 6FFF, 10FFF
Results	Gamma pass rates: 90-98% for 3%/3mm	Gamma pass rates: >95% after tuning
Inhomogeneity Handling	Performance affected by tissue inhomogeneity	Better performance for lung and complex inhomogeneous sites
Clinical Validation	Slight reduction in accuracy for complex cases	High accuracy across all complex plans, especially lung
Improvement/Innovation	-	ARLF parameter tuning improves dose agreement

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