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Fabrication of inhouse phantom to study the dosimetric accuracy of FF & FFF beam in for high energy photon beam

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Abstract
Aim: Present study was under taken to evaluate the performance of different algorithms for Flattening Filter Free (FFF) photon beams and flattening filter (FF) beams in three inhomogeneous mediums.
Materials and Method: Three Computed Tomography (CT) image sets of the CIRS phantom, containing ionisation chamber respectively in lung, bone and tissue regions, maintained in SAD setup were acquired. The corresponding Treatment Planning System (TPS) calculated and ionisation chamber measured doses at the centre of chamber (in the three mediums) were compared for flattened and non-flattened photon beams.
Results: The results was reported for photon energies 6MV, 10MV, 15MV, 6FFF and 10FFF at field sizes of 10x10 cm^2, and 15x15 cm^2. In Monte carlo algorithm the lung inhomogeneity shows the maximum dose variation was -3.6% of measured chamber dose in 10MVFFF photon energy for the field size 10X10 cm^2. In Collapse cone algorithm the lung inhomogeneity shows the maximum dose variation was 4.36% of measured chamber dose in 10MV photon energy for the field size 10X10 cm^2 whereas Pencil beam also shows highest dose variation in lung inhomogeneity was 4.99% of measured chamber dose in 10MV photon energy for the field size 15X15 cm^2. In lung structure, higher deviation was recorded by all the three algorithms.
Conclusion: Both, FF and FFF beams performed differently in Lung, water and bone mediums. The assessment of algorithms were conducted using the anthropomorphic phantom, therefore these finding may help in selection of appropriate algorithm for particular clinical settings in radiation delivery.

Keywords: CIRS thorax phantom, Monte Carlo, pencil beam convolution, collapsed cone convolution

Introduction
Over a period of more than a century, radiotherapy technology has developed tremendously with greater accuracy and faster dose delivery to patients. The performance of the algorithms employed for dose calculation has always attracted investigators because incorrect dose calculations can lead to uncertainty in the radiation dose distribution. In this line, both hardware and software technology has seen amazing transformations from 3DCRT, IMRT with flattening filter, volumetric arc therapy and currently IMRT without flattening filter technology. In this line, both hardware and software technology has seen astonishing developments including from 3DCRT to intensity modulated radiation therapy with flattening (volumetric-arc) to newer IMRT without flattening filter designs.
Radiotherapy involves different steps majorly imaging, contouring, planning, verification, delivery, follow-up etc. These all the steps are followed-up generally in all the cancer site(s) radiotherapy almost in same order using technology mentioned [1]. Error(s) in any one of the steps may propagate to the next step(s). Particularly the planning step deals with the organ delineation in CT images (virtual patients), dose calculation by set of instructions i.e. algorithm, with the maximum efforts on reproduction of all the significant physical events occurring in actual and capturing them useful in patient dose calculations. The accurate dose calculation is of great importance that could be understood by the fact that the data for these algorithms are initially obtained from the homogeneous stationary water phantom setup which are later applied in the real patient dose calculation with the numerous corrections applied to take care the differences between measured and real patient in terms of shape, size and density variations [2].

These algorithms basically take care of the various anatomical and compositional variations (i.e. density) of different patients for various aspects related to accurate dose calculations. A algorithm is said to better depending upon its ability to reproduce all physical events as a result of interaction of radiation occurring in real patients and to incorporate its contribution in to the dose calculations. The factor of uncertainty in dose calculation in flattened beam, taking care of the scattered and leakage radiation, becomes larger in presence of the inhomogeneity such as tissue bone junction, air cavity, air soft tissue border/junction compared to homogeneous static water phantom setup used in extraction of commissioning data for the Treatment Planning System (TPS). The recently introduced flattening filter free linear accelerator is gaining popularity due to its obvious features including increased dose rate and reduced treatment time. Treatment sites such as lung cancer are affected by continuous breathing and other factors that can lead to uncertainty in dose delivery [3]. The FFF beam technology reduces treatment time (due to higher dosing rates) and helps in dose delivery with increased accuracy and precision. Although the FFF beam emerged as a very popular technique, the performance of the algorithms used in dose calculations has been questioned from time to time, especially due to the very inhomogeneous nature of the radiation in the FFF beam. To be enough confident in its clinical applications, similar to FF beams, FFF should also be investigated for their algorithms performance in different mediums and densities [4]. Therefore, the present study was under taken to evaluate the performance of different algorithms for flattening filter free and flattened photon beams in three different inhomogeneities.

Method and Materials

CIRS Phantom: In the present study CIRS (Model 002LFC, computerized imaging reference Systems Inc., Norfolk, Virginia) phantom was used which is designed to access the algorithm performance and accuracy of dose delivery as well as for the CT Quality Assurance (QA) test. The phantom has dimensions of 30 cm both in length and width and thickness of 20 cm with compositions closed to the real human lung and bone structures. This Intensity Modulated Radiation Therapy (IMRT) phantom is designed in such a way that facilitates measurement of radiation dose using ready pack films and ionization chambers. The surface of the phantom comes with the three markers one middle and two lateral to the body respectively to match the phantom body with the three LASERs during scanning and irradiation as done in real patients clinical work flow. The phantom is lashed with the interchangeable dosimeter inserts in lung, bone and tissue simulating region in phantom body for the representation of structure pattern as in real human thorax. Before proceeding for the measurements using either of the dosimeters viz Gafchromic films or farmer chamber measurements using the solid water inserts are recommended for point dose verification and to cross check these other dosimeters readings. The CIRS (segmented) phantom used in the present study is provided in total ten inserts with two inserts in each of the two lung equivalent regions, one in bone representing spine and five in tissue equivalent regions of the phantom as shown in figure 1 to hold the standard dosimeters and customized dosimeters. For the evaluation of calculation accuracy of different algorithms, dose measurements were performed in these three density regions namely bone, lung and soft tissue using the interchangeable solid inserts.

Fig 1: CIRS Thorax phantom with ionization chamber

In this present study ionization chamber 0.6 cc (TN30013) (PTW, Freiburg, Germany) was employed for the point dose measurements. The chamber is designed for the absolute and depth dose measurements suitable for the energy range from Co-60 to 50 MV photons and 6 to 50 MeV electrons.

Commissioning of TPS

Monaco Treatment planning system commissioning done as per the requirement of data prescribed by Elekta Medical System Pvt ltd and all necessary Profiles, Depth dose scans, output factors etc were generated in a RFA (Radiation Field Analyser) using ion chamber as both reference and field. The absolute dose measurement was performed as per the IAEA TRS 398 protocol using PTW 30013 FC-65 farmer chamber in a water phantom with standard field size of 10 x10 cm^2. After complete beam modelling the TPS system is tested as per the TRS 430 protocol. For verification of point dose measurement in TPS, QA clinic was utilized and a single anterior beam was fired with 100MU and 10 x10 cm^2 field size and calculation was performed.

Method: Firstly, CIRS phantom was setup in SAD on CT (GE optima 580 w, USA) couch matching the three markers of plus sign on the phantom body with the help of the three room LASERS i.e. two lateral and one medial in similar fashion as done in case of real patient's setup work flow. Then farmer type 0.6cc ionisation chamber was placed inside the lung region provided in phantom using appropriate insert and CT scan images having slice thickness 2.5 mm were taken. The CT scan images were also acquired by changing the position of the chamber to bone (i.e. spine) and tissue equivalent regions by putting the insert holding the chamber in similar way as done previously [Fig 2].

After acquisition, all the three CT data sets send to the TPS console for the point dose calculations by three algorithms namely X-ray Voxel Monte Carlo (XVMC), Pencil beam (PB) and Collapsed Cone (CC) found in the Monaco V 5.11.03 (Elekta AB, Stockholm, Sweden) treatment planning System. Contouring of chamber cavity and other necessary steps were done at TPS console for the dose calculation at the centre of the chamber in both flattened and non-flattened photon beams of energy 6, 10 and 15 MV as shown in the Table 3 - 5. Dose calculated at the centre of the chamber were recorded for both the flat and non-flat photon beams in all the three regions.

Similarly, again same phantom setup was reproduced at the LINAC (VERSA HD, Elekta Medical System inc, Sweden) couch for the point dose measurements using the ionisation chambers of air volume 0.6 cc with chamber position exactly

as it was maintained at the CT console. These Ionisation chambers were connected to the PC Electrometer coupled with chamber. As performed in to the TPS, 100 MU were delivered in all the positions of inserts in lung, bone and tissue equivalent regions for 0.6 cc chambers. Using these electrometer readings, dose deposited for 100 MUs were measured by applying necessary Corrections factors for temperature, pressure, recombination, and polarization according to the Technical Report Series (TRS) 398.

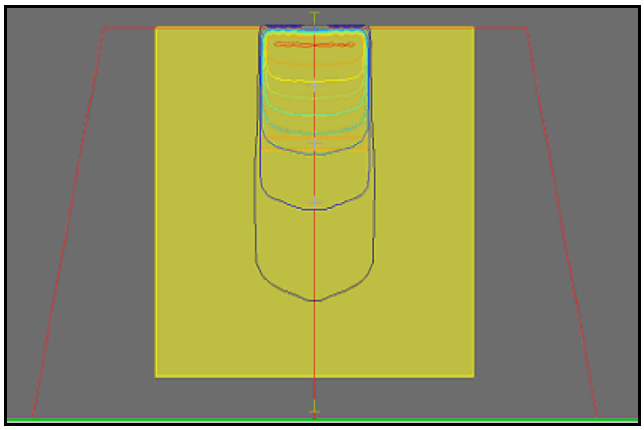

Fig 2: TPS calculation for 10x10 cm^2 using Fc-65 Ionization chamber

Results

In the present study Monte Carlo Treatment planning system (V 5.11.03) were used for the qualitative assessment of uncertainty in its performance in case of three mediums having fairly different density viz Bone equivalent medium of density (1.6 gm/cm^3), Plastic water (1.039 gm/cm^3) and lung equivalent medium (0.21 gm/cm^3) in case of flattened and non-flattened beams. Before taking the observation, it was necessary to examine the performance of TPS in homogeneous water phantom which was listed in Table 1. the TPS dose comparison in homogeneous phantom using Fc-65 ionization chamber for cental axis measurement. The dose was also calculated in TPS with different algorithms. In Monte carlo algorithm dose calculation parameter was set with 0.5% statistical uncertainty per calculation. So, the actual results were less than 0.5% if dose obtained were subtracting to this 0.5% statistical uncertainty after dose calculations. The leakage through MLC was measured using the standard prescribed setup and procedures utilized for the beam modelling later installed in TPS. The values of average and maximum leakage of radiation (photon) for the energy values under investigation are listed in Table 2.

Table 1: TPS dose comparison in homogeneous phantom using Fc-65 ionization chamber for cental axis measurement SAD setup, Depth = 10 cm, FS = 10 cm×10 cm, MU = 200.

Energy (MV)	Chamber Dose (cGy)	TPS Dose (cGy)			%age Variation		
		P.B	C.C	M.C	P.B	C.C	M.C
6	164.08	163.7	163.4	165.7	0.23	0.41	-0.987
10	175.38	173.9	174.3	174.5	0.84	0.62	0.50
15	183.95	185.4	184.9	183.9	-0.78	-0.51	0.027
6FFF	162.22	161.0	-	162.2	0.75	-	0.012
10FFF	174.52	172.9	-	174.2	0.93	-	0.18

Table 2: Results of Leakage measurement for 6, 10 and 15 MV photon beams

Sr. No	Energy Value	Maximum Leakage (%)	Average leakage (%)
1	6	0.1163	0.0446
2	10	0.1201	0.0481
3	15	0.1346	0.0516

For quantitative evaluation of the performance of the algorithms, both calculated and measured point dose values were recorded. Table 3, 4 and 5 depicts the absolute point dose measured by the farmer chamber of 0.6 cc and dose calculated by various algorithms at the same point together with the% variation in corresponding calculated values. This variation is actually to give amplitude of% difference between calculated doses with respect to (w.r.t.) respective measured dose values. The% variation was calculated as follows:

Dose difference (%) = (Dmeas−Dcal/Dcalc)×100

(A) Pencil Beam Convolution

In the bone inhomogeneity as shown in table 3, the maximum dose variation for PB algorithm predicted was 4.88% of measured chamber dose in 10MV photon energy for the field size 10X10 cm^2.

In the water inhomogeneity as shown in table 4, the maximum dose variation for PB algorithm predicted was 2.35% of measured chamber dose in 10MV photon energy for the field size 15X15 cm^2.

In the lung inhomogeneity as shown in table 5, the maximum dose variation for PB algorithm predicted was 4.99% of measured chamber dose in 10MV photon energy for the field size 15X15 cm^2.

In pencil Beam Convolution 10MV energy shows the maximum dose variation in all the three inhomogeneities.

Table 3: TPS calculated and o.6 cc ionisation chamber measured point doses corresponding to 100 MU in Bone equivalent medium

Energy	6 MV (Dose cGy)			10 MV (Dose cGy)			15MV (Dose cGy)			6 MV FFF (Dose cGy)		10 MV FFF (Dose cGy)	
Field Size	Algorithms			Algorithms			Algorithms			Algorithms		Algorithms	
	M.C	C.C	P.B	M.C	C.C	P.B	M.C	C.C	P.B	M.C	P.B	M.C	P.B
10X10	64.7	64.3	65.0	73.7	72.8	72.1	81.9	79.2	78.3	63.8	63.1	72.5	70.0
Chamber Dose	66.08			75.62			80.53			64.53		72.84	
% Variation	2.1	2.76	1.66	2.6	3.87	4.88	-1.67	1.68	2.84	1.14	2.26	0.47	4.05
15X15	69.7	68.9	70.3	77.4	77	75.9	85.0	83.4	82.1	66.9	66.9	74.9	72.5
Chamber Dose	70.1			79.26			84.01			67.31		75.02	
% Variation	0.66	1.83	-0.2	2.4	2.93	4.42	-1.16	0.73	2.32	0.61	0.61	0.16	3.47

Table 4: TPS calculated and o.6 cc ionisation chamber measured point doses corresponding to 100 MU in water equivalent medium

Energy	6 MV (Dose cGy)			10 MV (Dose cGy)			15MV (Dose cGy)			6 MV FFF (Dose cGy)		10 MV FFF (Dose cGy)	
Field Size	Algorithms			Algorithms			Algorithms			Algorithms		Algorithms	
	M.C	C.C	P.B	M.C	C.C	P.B	M.C	C.C	P.B	M.C	P.B	M.C	P.B
10X10	90.5	89.7	90.7	95.2	93.1	94.2	99.8	97.9	99.2	90.9	89.5	95.7	93.5
Chamber Dose	90.74			95.95			99.25			89.10		94.07	
% Variation	0.26	1.16	0.04	0.78	3.0	1.85	-0.55	1.37	0.05	-1.98	-0.44	-1.70	0.61
15X15	94.6	93.3	94.3	98.4	96.5	96.8	102.9	101.4	102	92.9	91.8	97.2	94.6
Chamber Dose	94.1			99.08			102.1			91.27		95.57	
% Variation	-0.53	0.85	-0.21	0.69	2.67	2.35	-0.77	0.69	0.09	-1.75	-0.57	-1.67	1.02

Table 5: TPS calculated and o.6 cc ionisation chamber measured point doses corresponding to 100 MU in Lung equivalent medium

Energy	6 MV (Dose cGy)			10 MV (Dose cGy)			15MV (Dose cGy)			6 MV FFF (Dose cGy)		10 MV FF (Dose cGy)	
Field Size	Algorithms			Algorithms			Algorithms			Algorithms		Algorithms	
	M.C	C.C	P.B	M.C	C.C	P.B	M.C	C.C	P.B	M.C	P.B	M.C	P.B
10X10	97.2	92.8	92.7	100.3	95.2	96.3	103.2	99.2	99.3	96.1	92.1	98.0	93.9
Chamber Dose	95.86			98.58			99.94			93.32		94.44	
% Variation	-1.37	3.3	3.4	-1.71	3.55	2.36	-3.1	0.74	0.64	-2.89	1.32	-3.6	0.57
15X15	101.7	97.2	96.2	105.1	99.5	98.9	109.0	104.0	104.3	99.3	94.7	100.5	96.7
Chamber Dose	100.28			103.84			105.75			96.41		97.77	
% Variation	-1.39	3.16	4.24	-1.19	4.36	4.99	-2.98	1.68	1.39	-2.91	1.81	-2.72	1.11

(B) Collapse Cone Convolution

In the bone inhomogeneity as shown in table 3, the maximum dose variation for CC algorithm predicted was 3.87% of measured chamber dose in 10MV photon energy for the field size 10X10 cm^2.

In the water inhomogeneity as shown in table 4, the maximum dose variation for CC algorithm predicted was 3.0% of measured chamber dose in 10MV photon energy for the field size 10X10 cm^2.

In the lung inhomogeneity as shown in table 5, the maximum dose variation for CC algorithm predicted was 4.36% of measured chamber dose in 10MV photon energy for the field size 10X10 cm^2.

In CCC 10MV energy shows the maximum dose variation in all the three inhomogeneities. There was no CC algorithm commissioned in flattening free filter energies in TPS, so no calculations were done.

(C) Monte Carlo Calculation

In the bone inhomogeneity as shown in table 3, the maximum dose variation for MC algorithm predicted was 2.6% of measured chamber dose in 10MV photon energy for the field size 10X10 cm^2.

In the water inhomogeneity as shown in table 4, the maximum dose variation for MC algorithm predicted was -1.98% of measured chamber dose in 6MVFFF photon energy for the field size 10X10 cm^2.

In the lung inhomogeneity as shown in table 5, the maximum dose variation for MC algorithm predicted was -3.6% of measured chamber dose in 10MVFFF photon energy for the field size 10X10 cm^2.

Discussion

CIRS Semi Anthropomorphic Phantom

In the present study, the authors attempted to assess the performance of the popular TPS algorithms with respect to the FFF beam, which is equipped with the unique advantages of high dose rates to help reduce the deteriorating effects of motion in radiation delivery and its consequences. Dose calculated by different algorithms for both the, FF and FFF, photon beams were analysed for their accuracy in different mediums. Compared to other studies with similar objectives using a homogeneous and flat surface medium of different densities only, the experimental setup used in the present study is quite different approaching towards the real clinical settings. This difference always creates doubt in its application in routine clinical practices [5]. However, the present study used semi anthropomorphic phantom which represents the average human thorax shape in terms of weight, body curvature found in thorax region and partially in composition, too.

Algorithms and its Clinical impact on FF and FFF beams

Performances of algorithms has a vital role in fate of the accurate radiation dose delivery and are taken to be as heart of the TPSs performance in contouring, dose calculation taking care of all the variations in composition of organs of interest under the radiation beam traversing the body regions. Algorithms are basically different in terms of their ability how closely it is taking care of infinitesimal density variation and in turn in the dose deposition clubbing the cascades of events e.g. ionisation, scattering, attenuation, secondary production and a number of processes. Over the past two decades, a remarkable development has taken place in the prediction of dose deposited by algorithms as well as in its speed. Out of many, Monte Carlo dose calculation algorithms are taken to be gold standard. The dose calculation process is very complicated process due to anatomical, physiological and compositional variation in the human body due to the prime reason of instruction sets of these algorithms are derived from the homogeneous still and uniform density mediums, known as water phantom or simply phantoms. In this study, with the aim of as similar experimental setup as of human body, anthropomorphic phantom was used having variation in density. Also, a number of algorithms such as CC, PB as well as Monte Carlo XVMC were used for the assessment of their performance, both, in the flattened and non-flattened beams for various clinically practiced beam energies.

The results of the present study indicates a larger deviation between the calculated and measured data, which could be as high as 6.25% in water in the FFF beams of demission 5x5 cm^2 as shown in table 4. The FFF beams have high dose rate,

around 3-4 fold, that of the FF beams and very inhomogeneous in nature. ICRU recommend a tolerance of 5% uncercertinty in dose calculation accuracy which have been reiterated and observed by many of the researchers however, comparatively low literature are available for the FFF beams [6]. Not limited to this much deviation, in water medium, even larger deviation (~13%) have been recorded in lung equivalent medium in FFF beams followed by FF beams (5x5 cm^2). One of the interesting result, opposing the fact validated by number of studies that MC algorithms are gold standard for simulation of particle transport and dose predictions, as anticipated and motivation fact to conduct this study i.e. any change in performance of TPS in FFF beams, to note is in context of bone equivalent medium where lowest difference between calculated and measured values were found [7]. This ambiguity can be attributed to the fact that

MC based TPSs are facilitating the absorbed dose details in medium of inhomogeneities encountered in radiotherapy well within 2-3% uncertainty, which are far better than the analytical algorithms [8, 9]. Other source of these uncertainties (i.e.% deviations in Table 3, 4, 5) may belongs to the mode of dose calculation i.e. dose to medium or dose to water in case of MC XVMC although the default mode is the dose to medium [10]. The approach of dose to medium is peculiarly dependent on the density details provided by the CT scan. For the dose determination deposited in the medium these CT details (followed in MC TPS) pass though the complex process of density conversion and any uncertainty in CT detail would lead to error in doe calculation [11, 12]. The present study employed point dose (along central axis) assessment of TPS using single beams 5x5, 10x10, 15x15 cm^2 dimensions. There are number of studies similar to Narayanasamy *et al*. in which dosimetric validation of the MC based TPS including the FFF beams was performed in clinical settings in terms of Three-Dimensional Conformal Radiation Therapy (3DCRT), IMRT and Volumetric Modulated Arc Therapy (VMAT) and have reported the accuracy and reported 3% agreement between measured and calculated dose with a passing rate of around 94.7% based on 2% dose difference and 2 mm distance-to-agreement criteria in IMRT test fields [13].

In the present study also, the Monaco TPS validation was performed following the international guidelines for the advanced TPS equipped with FF and FFF features [14, 15].

Other than MC, CC and PB were also assessed for their performance in mediums of water, lung and bone density equivalence. PB and MC were assessed for the FFF beams having energies 6 and 10 MV. In this study PB was always found to be of largely under estimating in bone medium opposite to the finding of Chopra *et al*'s study with the aim of assessment of TPS performance in inhomogeneous medium using the phantom comprised of flat slabs of water, lung equivalent (cork) materials flat slabs of bone equivalent material. However PB (FF beams) was reported to be overestimating in lung equivalent mediums similar to Chopra *et al*. observations [16]. Also, CC algorithms were investigated in this study (for FF beams only) for its dose calculation accuracy in these inhomogeneities. As clear from the Table 3, 4, 5 CC; is fairly good if computation speed and efficiency of through put of the TPS is compared over the computation time and accuracy of the MC based algorithm. Although, the present work is based on single beam point (along central axis) observations, similarly Snyder *et al* in their work under took for the investigation of Monaco TPS's calculation accuracy in inhomogeneities and treatment techniques such as VMAT, SBRT etc presenting commissioning and validation of Monaco TPS for Elekta VersaHD Linac [17, 18, 19]. Out of three mediums, as depicted in table [3, 4, 5], the% deviation between measured and calculated values, lung has been most complex and challenging for the accurate dose calculation. Out of many variables studied in this work viz energy, field size, nature of beams FF or FFF, inhomogeneity, pertaining to dose calculation accuracy the authors could not found any common trends/feature in both the FF and FFF describing deviation between measured and calculated dose except the dimension of beams. It is obvious that similar to FF, as have studied in number of studies in FF beams, in FFF beams also it was found that deviation was decreasing in nature with field size.

Conclusion

In the present study there algorithms were assessed for their ability of accurate dose calculation in there different mediums covering almost range of density spectrum i.e. lung, water and bone for both FF and FFF photon beams. Both, FF and FFF beams performed differently in Lung, water and bone mediums. The assessment of algorithms were conducted using the anthropomorphic phantom, representing the average human thorax, therefore these finding may help in selection of appropriate algorithm for particular clinical settings in terms of beam energy-type (FF or FFF) and tumor site for radiation delivery. The findings may also support the requirement of stress to be invested in day to day QA procedure depending the site of tumor and photon beam(s) used in radiotherapy. It can also be concluded that lung and other low density clinical environment under radiation delivery are complex and challenging in accurate radiation delivery especially with FFF beams. Therefore, one has to balance the speed of radiation delivery, motion management over the accuracy.

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Conflict of Interest

None

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