ABSTRACT

The medical linear accelerator (LINAC) is a device that uses high frequency microwaves to accelerate electrons generated by electron gun to high energies through an accelerator tube. These electrons are allowed to strike a high atomic number (Z) target for production of high energy x-rays. In general, such LINAC produce electron beams of energies between 4 to 25 Mega-electron Volts (MeV) and photon beams of nominal energies 6 Mega Volt (MV), 10 MV and 15 MV. This LINAC is used to treat varieties of cancer cases utilizing electron as well as photon beams. The conventional LINAC uses a conically shaped flattening filter (FF) made up of a high Z material in the photon beam delivery mode and acts as an attenuator, the beam hardener and the scatterer. It is located between the primary collimator and the monitor chamber and its main role is to compensate the non-uniformity of photon beam dose variation across the radiation field. However, it may not be necessary for the certain type of advanced radiotherapy treatments. The advanced beam therapy techniques such as stereotactic radio surgery/radiotherapy (SRS/SRT) and stereotactic body radiotherapy (SBRT) where inhomogeneous dose distributions are applied and intensity modulated radiotherapy (IMRT) where varying fluence pattern across the beam are delivered, have stimulated the increasing interest in operating standard LINAC in a flattening filter free (FFF) mode.

A Standard LINAC can be used for generating photon beams either with FF or without FF. The conically shaped FF made of a high Z material is located in the gantry of the LINAC, between the primary collimator and the monitor chamber, and its main function is to flatten the output dose so that it has a uniform beam profile at the reference depth. Besides the beam uniformity, some disadvantages of FF for advanced radiotherapy techniques are that it acts as an attenuator, reduces dose rate, and is a major cause of head scattering. The removal of FF from the path of X-ray beam results in 2-4 times increase in dose rate, inhomogeneous beam profile and a decrease in head scattering. The higher dose rates and therefore a shorter delivery time of FFF beam would keep the patient on the treatment couch for a shorter period of time. Thus, giving more comfort to the patient and decreasing the chances of intra-fractional setup inaccuracies. These are critical elements in the techniques used for treatment of small lesion such as SBRT because of the usage of high fraction doses

and of small margins for planned target volume (PTV), thus requiring very high accuracy and precision. A number of theoretical and experimental studies related to the clinical implementation of FFF beams demonstrated their suitability and superiority over FF photon beams.

The FFs have been considered as an integral part of the treatment head of a LINAC for more than 50 years and reasons for the longstanding use are, however, historical ones. In the 1991, O'Brien et al studied 6 MV FFF photon beams and main interest of the study was the need to reduce radiosurgery treatment delivery time. Several other studies were performed after this and were mainly motivated with research interest in the characteristics of FFF beam. In 2004, Fu et al investigated the effect of removing the flattening filter on reducing IMRT delivery time in a treatment planning study. In 2006 onwards, MD Anderson and other groups began publishing. Their outcomes suggest that with a FFF accelerator better radiation treatments can be developed, with shorter treatment times and lesser doses to healthy tissues. In 2010, Varian Medical Systems developed the TrueBeam LINAC equipped with both FF and FFF photon beams, and the product was made available for commercial uses from then onwards. The development of an FFF beam mode in the LINAC is thought to provide additional benefits to SBRT. During 2010 to 2021, hundreds of medical linear accelerators with FFF features have been installed worldwide. The primary advantage of FFF beam is the ability to use much higher dose rates, which results in a shorter delivery time. Shortening the delivery time would keep the patient on the treatment table for a shorter period of time. As a result, it provides more comfort to the patient and also reduces the chances of inaccuracy due to movement of the patient. Because of the use of high fraction doses and small tumor margins, these are critical elements in SBRT to provide very high precision in treatment delivery. With these advantages in mind, many researchers are still working to establish the general guidelines regarding the acceptance, commissioning, quality assurance, planning and pre-treatment verification of FFF photon beam so that it becomes a full replacement to the FF photon beam.

Therefore, this study aimed to evaluate three aspects of FFF photon beams, namely small field dosimetry, treatment planning, and pretreatment verification, in order to increase the available data on this topic. The first one is concerned with the measurement of small fields of a 6 MV FFF beam using different detectors. The second aspect is aimed to dosimerically evaluate the different planning techniques

based on FFF beam for central and peripheral lung as well as spinal SBRT. The third aspect is concerned with the pretreatment dose verification procedures for SBRT using different patient specific quality assurance (QA) tools.

A TrueBeam LINAC (Varian Medical Systems, Inc., Palo Alto, CA, USA) capable of delivering both FF and FFF photon beams was used. A 6 MV FFF photon beam was used for the measurements of dosimetric parameters and for treatment planning. The five detectors used were SNC125c (ionization chamber, Sun Nuclear Corporation), PinPoint (ionization chamber, PTW 31014), EDGE (diode detector, Sun Nuclear Corporation), EBT3 (Gafchromic films, Ashland Advanced Materials), and TLD-100 (TLD chips, Harshaw Chemical Company). All measurements were performed as per the International Atomic Energy Agency TRS 483 protocol. RANDO phantom computed tomography (CT) images were used for treatment planning. Gross tumor volumes (GTVs) were delineated in the central and peripheral lung locations. PTV was determined by adding a 5 mm margin to the GTV. A total of 24 PTVs, 12 per lung location, were delineated. These PTVs were a set of 12 distinct tumor sizes between 3.85 cc and 79.06 cc, with the same geometric center and with varying volumes. Both tumor locations were contoured with the same set of PTVs. Three dimensional conformal radiotherapy (3DCRT), IMRT, and volumetric modulated arc therapy (VMAT) plans were generated using a 6-MV FFF photon beam. Dose calculations for all plans were performed using the anisotropic analytical algorithm (AAA) and Acuros XB algorithms. The accuracy of the algorithms was validated using the dose measured in a CIRS thorax phantom (model 002LFC; Computerized Imaging Reference Systems, Inc. [CIRS], Norfolk, VA, USA). For spinal SBRT, two major sections of spine i.e. thoracic and lumbar spines were selected for target delineation. A total of eight PTVs were contoured on RANDO phantom CT images, with four PTVs per section of the spine (thoracic and lumbar). VMAT plans for each PTV were generated using four different beam arrangement techniques with a 6-MV FFF photon beam, two of which were mono-isocentric (MI) and two of which were dual-isocentric (DI). Dose calculations for all plans were performed using the Acuros XB algorithm. Pre-treatment dose verification was carried out for VMAT based SBRT plans using MapCHECK 3, ArcCHECK and Portal Dosimetry system.

In this study, we determined the output factors of small fields according to TRS 483 along with their measurement uncertainties. For comparison, we first

estimated the output factors, as traditionally performed by users in the absence of TRS 483 correction factors. The output factors estimated as the ratio of detector readings with SNC125c, PinPoint, TLD-100, EBT3, and EDGE for field sizes between 2 cm × 2 cm and 6 cm × 6 cm were found to be in good agreement (RSD < 0.70%). The remaining field sizes 0.6 cm × 0.6 cm and 1.0 cm × 1.0 cm showed significant variation with RSD of 11.83% and 2.93%, respectively. SNC125c showed the lowest value of the output factor for the smallest field size (≤ 1 cm × 1 cm), while the largest value was recorded by the EDGE detector, and the difference between the two values was the highest. We found that after applying the correction factors suggested by published studies to our measurements, the smallest fields 0.6 cm × 0.6 cm and 1.0 cm × 1.0 cm showed minimal variation with RSD of 1.97% and 1.05%, respectively, and remaining fields were found to be in good agreement with RSD of less than 0.30%.

A significant difference in penumbra was observed between different detectors. The beam profiles of the small field measured using the EBT3 and EDGE showed the smallest penumbra, and the difference between the two detectors was negligible. The measurement from each detector showed that the surface dose increased with increasing field size above 2 cm × 2 cm, whereas for decreasing field sizes below 2 cm × 2 cm, the surface dose increased. These results are consistent with those of previous studies using radiochromic films, ionization chambers, and diodes. It was found that that for small field sizes of 0.6 cm × 0.6 cm to 6 cm × 6 cm, the SNC125c showed the highest value for surface dose, whereas the lowest value was obtained with the EBT3. The PDD of the 6 MV FFF beam was found to correspond to that of a standard 4–5 MV FF beam. Detector to detector variation of D10 (PDD at 10 cm depth) for 0.6 cm × 0.6 cm field size was noticeable (RSD = 1.80%), whereas other field sizes showed negligible deviation (RSD ≤ 0.62).

The planning characteristics of lung and spinal SBRT were evaluated for different planning techniques. The comparison of FFF-3DCRT, FFF-IMRT, and FFF-VMAT planning techniques for the SBRT of lung tumors showed that both the FFF-VMAT and FFF-IMRT plans provided an improved conformal dose of PTV than did FFF-3DCRT for peripheral and central lung PTVs. The conformity of the PTV dose in the FFF-VMAT plans was slightly improved compared to that of FFF-IMRT. Similar results were reported in a previous study. The conformity index (CI) of the FFF-VMAT, FFF-IMRT, and FFF-3DCRT plans was within the clinically acceptable

limit (CI ≤1.2) specified in the RTOG protocols, excluding minor deviations in the CI (CI ≤1.5) for the FFF-3DCRT plans for the smallest PTVs.

The high dose volume (HDV), low dose location (D2cm), and homogeneity index (HI) improved with FFF-VMAT compared to FFF-IMRT and FFF-3DCRT, while low dose volume (R50%) and gradient index (GI) showed improvement with FFF-3DCRT. Compared with FFF-3DCRT, a drastic decrease in the mean treatment time (TT) value was observed with FFF-VMAT for different lung sites between 57.09 % and 60.39 %, while with FFF-IMRT it increased between 10.78 % and 17.49 %. The dose calculation with Acuros XB was found to be superior to that of AAA. FFF-VMAT provided clear dose-sparing advantages to organ at risks (OARs) among all treatment planning techniques, except for the V20 (volume receiving 20 Gy or more) of the lung dose being significantly lower for the FFF-3DCRT plans due to the non-coplanar beam arrangement.

The dosimetric indices were compared between different beam arrangement techniques for spinal SBRT planning, including spinal cord avoidance, PTV dose coverage, conformity, homogeneity, and gradient index. The study found that when non-contiguous spinal lesions are widely spaced, it may be more effective to use 4-Arcs DI to generate a better HI and GI, whereas 2-Arcs MI was beneficial for closely spaced lesions. Furthermore, the use of more arcs with a dual isocentre reduced the volume of partial cord receiving 10 Gy (V_{10Gy}), maximum dose to 0.03 cc of partial cord ($D_{0.03cc}$), and monitor units (MUs). The results showed that DI has a higher plan quality than MI for treating non-contiguous spine SBRT, with better homogeneity and a lower dose to the spinal cord, as well as comparable tumour coverage, delivery accuracy, and adequate tumour coverage. 4-Arcs DI had the sharpest dose falloff and achieved the lowest overall spinal cord doses at the expense of twice the treatment time as 2Arcs-MI.

The pretreatment dose verification for SBRT plans were performed using MapCHECK 3, ArcCHECK, Portal Dosimetry, and PerFRACTION. The percentage global and local gamma passing rates were used to analyse the pretreatment quality assurance results. When compared to other pretreatment verification tools, the portal dosimetry had the highest global and local gamma pass rates. When it comes to global gamma passing rates that meet the 3%/3 mm criterion, only comparisons between portal dosimetry and ArcCHECK or MapCHECK 3 were statistically different ($p < 0.05$). On the other hand, the results of the local gamma passing rate showed that all

four pretreatment verification tools were statistically different from each other ($p < 0.05$) in most cases. However, portal dosimetry and PerFRACTION yielded identical results for the 3%/3 mm criterion, and the same is true between ArcCHECK and MapCHECK 3. When the gamma criteria were reduced to 3%/2 mm, 2%/3 mm, 2%/2 mm, and 1%/1 mm, the results showed that the four devices were statistically different ($p < 0.05$) in most cases.

The study concludes that the PinPoint, EBT3, TLD-100, and EDGE appear to be the detectors of choice for small-field output factor measurements. EDGE and EBT3 are optimal for measuring beam profiles. EBT3, PinPoint, and EDGE can be selected for depth dose measurements, and EBT3 is suitable for surface dose estimation. Based on the comparison of dosimetric indices in this study, FFF-VMAT provides a superior treatment plan to FFF-IMRT and FFF-3DCRT in the treatment of peripheral and central lung PTVs. DI has a higher plan quality than MI for treating non-contiguous spine SBRT, with better homogeneity and a lower dose to the spinal cord, as well as comparable tumour coverage, delivery accuracy, and adequate tumour coverage. 4-Arcs DI had the sharpest dose falloff and achieved the lowest overall spinal cord doses at the expense of twice the treatment time as 2Arcs-MI. The results of pre-treatment verification indicate that setting the same limit for all the four pretreatment verification tools is less accurate than selecting an acceptable gamma passing rate based on the correlation between various pretreatment verification tools.

Future research studied on this topic using higher energy FFF beams (greater than 6 MV FFF) and a different set of detectors may be useful in the development of guidelines for selecting a detector suitable for measuring a specific dosimetric parameter at those energies. In addition to this, we have chosen an anthropomorphic phantom over real patient CT datasets because, this allowed for a highly consistent set of tumors for SBRT planning. Future studies with higher energy FFF beams using current treatment planning methodology may provide some improved results for lung and spinal SBRT. In the future, other commercially available pretreatment devices for FFF beam-based SBRT can be investigated, which will improve the appropriateness of dose verification procedures in FFF photon beam.