The characteristics of small field beam quality and output factor of 6 MV FFF

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Abstract. Flattening filter free linear accelerator (FFF LINAC) has been installed in Indonesia. To ensure the accuracy of FFF irradiation, we evaluate the characteristic of FFF in regular and small fields. We employed the Monte Carlo (MC) simulation of FFF LINAC 6 MV as a standard reference in this study. Then, we compared the calculation of FFF beam at central and lateral axis to the measurement and TPS at 10×10, 1×1, 2×2, 3×3, 4×4 cm² field sizes. Output factor (OF) and beam quality such that TPR_{20,10} and penumbra of FFF LINAC were evaluated. TPR_{20,10}(S) for 10×10 cm² was 0.01 differ between MC and measurement whereas it varied from 0.588 to 0.703 for small fields. Dose difference of lateral axis was agreed within 3% except for the penumbra region. Output factor of small fields measurement indicated that field size of 1×1 cm² had a large discrepancy to MC according to this works. The TPR_{20,10}(10) of MC, TPS, and measurement was not a significant difference, while the OF was tending to a large deviation in 1×1 cm². The results showed that our FFF LINAC could be used for small field until 2×2 cm².

1. Introduction
Modern linear accelerator (LINAC) applied a sophisticated technique called intensity modulated radiation therapy (IMRT) as a standard cancer treatment using photon irradiation. This technique implemented a non-uniform fluence energy at the target volume in contrast with 3-dimensional conformal radiotherapy (3D-CRT). As a result, the idea of removing the flattening filter form head LINAC was rapidly developed. The advantage of removing flattening filter or called flattening filter free (FFF) is increasing the dose rate due to the absence of a main scatter contributor from head LINAC which provided a fast dose delivery to target [1]. Furthermore, several derivative techniques such as stereotactic radiation surgery (SRS) and stereotactic body radiation therapy (SBRT) are using small field irradiation in which the flattened dose distribution is independent to flattening filter [2]. The main challenge about small field irradiation is the lateral disequilibrium phenomenon on several ionization chambers in which could be effected to the accuracy of the calculated dose in radiation treatment planning system (TPS) [3].

As an impact of losing head scatter, the photon characteristics of FFF LINAC is different from the flattening filter (FF) LINAC. Several studies have been shown some differences of photon characteristics on energy spectrum, percentage depth dose (PDD), surface dose, profile, penumbra, and output factor by using measurement and Monte Carlo (MC) simulation [1–8]. Previous studies showed that the PDD of FFF LINAC had a stepper dose fall at the exponential region. In FFF LINAC, higher surface dose was also confirmed in contrast to FF LINAC. However, the surface dose which had a strong correlation with dose at maximum depth (d_{max}) in this modality was less depended on the change of irradiation field size due to the balance of beam hardening and scatter radiation effects [7–9]. The concept of beam profile for FFF LINAC was redefined by Pönisch, et al at large beam irradiation. Moreover, an inflection point was introduced to analyze the full width half maximum (FWHM) and beam penumbra [10,11]. However, for small field size, there was not a significant difference of beam profile trend between FF and FFF LINAC inside the opened beam collimator [7,12].
2. Materials and Methods

2.1. Linear accelerator
A Varian Trilogy (Varian Medical System, Palo Alto US) accelerator with modification to delivery FFF beam at Pasar Minggu Regional General Hospital (Jakarta, Indonesia) was used in this work. We irradiated water tank phantom which used for measurement of PDDs, profiles and OFs of regular and small fields with 6 MV FFF beam energy at 1120 MU/min. Head LINAC of the MC simulation was designed from Varian Monte Carlo Data Package for LINAC C-series with replacing of flattening filter to FakeBeam filter designed by Rodriguez et al [14,15].

2.2. Measurement Condition
Each measurements was done using open field method of 10×10, 4×4, 3×3, 2×2, and 1×1 cm² and source to surface distance (SSD) of 100 cm. We performed the measurements using ionization chamber CC13 which had 0.13 cc active volume. CC13 detector was positioned inside the Blue Phantom2 and connected to MyQA Accept System (ScanditronixWellhofer GmbH, Schwarzenbruck, Germany). The PDDs was scanned until 30 cm depth and then the detector was moved to 10 cm depth to measure the profiles at crossline direction and OFs at the center of axis. In order to examine the effect of lateral disequilibrium of small field irradiation, we compared the CC13 measurement with pinpoint chamber PTW-31016 which had active volume of 0.016 cc and Gafchromic EBT3 film (Ashland ISP Advanced Materials, NJ, USA). The films was sandwiched at 10 cm depth of solid water materials. The OFs for small volume detector was defined by daisy-chain method introduced by Alfonso, et al [16].

2.3. Monte Carlo Simulation Condition
We accomplished Monte Carlo on EG5nrc user code which constructed of BEAMnrc and DOSXYZnrc to simulate the particle interaction in head LINAC and water phantom, respectively. The head LINAC was built from 8 geometry structures, i.e. target, primary collimator, vacuum glass, modified filter, monitor chambers, mirror, jaws, and air until SSD 100 cm. Head LINAC in our experiment was divided into static and dynamic region which were the structure from target to mirror and jaws to phantom surface, respectively. We run the simulation with 1×10⁶ and 4×10⁸ particle histories at static and dynamic region. Radiation field sizes of the MC simulation was generated on dynamic region which shaped by jaws. The photon cut off energy (PCUT) was 0.01 MeV and electron cut off energy (ECUT) was 0.70 MeV included its rest mass. Furthermore, we used direct bremsstrahlung split (DBS) method with 10 cm radius to reduce the simulation time without losing any dosimetric interest.

Photon beam was generated on MC simulation by bombarded target with pencil beam electron. This electron had kinetic energy and FWHM of 6.2 MeV and 0.2 cm, respectively. The phasespace files of both regular and small field sizes at the end of SSD was collected and then became the particle fluence source of water phantom. The simulated water phantom was built from 128 group of voxels in 3D-
direction with a voxel size of 0.25×0.25×0.25 cm$^3$ and 0.0375 × 0.0375 × 0.25 cm$^3$ to cover regular and small fields, respectively. The particle histories was 4×10$^8$ and other parameters were set same as head LINAC simulation. We evaluated 10×10 cm$^2$ of PDD and profile at 10 cm depth MC to measurement in order to adjust the kinetic energy and FWHM of electron source in this simulation. Dose difference between MC simulation and measurement was performed according to equation (1),

$$\%D = \frac{D_s - D_{ml}}{D_s} \times 100\%$$

(1)

where $\%D$ is dose difference, $D_s$ and $D_{ml}$ are simulated and measured or TPS dose, respectively. An agreement of dose difference form both MC and measurement was set under 3%.

Theoretically, the TPR$_{20,10}(S)$ was obtained from the direct measurement of depth 20 cm and 10 cm at water phantom with fix source to detector distance (SDD) 100 cm for any $S$ fields. Practically, for 10×10 cm$^2$ beam, TPR$_{20,10}(10)$ was easily calculated from empirical formula described in IAEA TRS 398 [17] which facilitated medical physicist to do only PDD measurement. However, it was not sure to implement the formula in small fields irradiation. Further, Sauer and Palmans were derived formulas of quality index for photon beams on method to convert PDD to TPR for any arbitrary field until 4×4 cm$^2$ [18,19]. In this work, we forced those formulas to calculated TPR$_{20,10}$ at 4×4, 3×3, 2×2, and 1×1 cm$^2$ and then compared with direct measurement, TPS calculation, and MC calculation.

### 3. Result and Discussion

Kinetic energy and full-width half maximum (FWHM) of the electron source of MC simulation FFF LINAC 6 MV were 6.2 MeV and 0.20 cm, respectively. The average deviation of relative dose between MC and CC13 PDD at 10×10 cm$^2$ was 0.04% (-1.42 to 12.8%) and for MC to TPS was -0.17% (-1.74 to 4.76%) in which the maximum difference occurred at the build-up region. On the other hand, the mean dose difference for beam profile were 0.61% (-1.02 to 2.40%) and 0.34 (-1.11 to 1.89%) between MC-measurement and MC-TPS, respectively.

#### Table 1. TPR$_{20,10}$ at regular and small fields for 6 MV FFF evaluated with SSD 100 cm and SSD 100 cm technique.

| Modality | Field size (cm$^2$) | SSD 100 cm | SSD 100 cm | TPR$_{20,10}(S)$ | TPR$_{20,10}(10)$ | TPR$_{20,10}(S)$ | TPR$_{20,10}(10)$ |
|----------|-------------------|------------|------------|-----------------|-----------------|-----------------|-----------------|
| Meas$^c$ | 10×10             | 0.640      | -          | -               | 0.647           | 1.20            |                 |
|          | 4×4               | 0.592      | 0.629      | 0.682           | 0.591           | 1.62            |                 |
|          | 3×3               | 0.589      | 0.634      | 0.679           | 0.585           | 1.45            |                 |
|          | 2×2               | 0.588      | 0.641      | 0.676           | 0.581           | 2.33            |                 |
|          | 1×1               | 0.590      | 0.650      | 0.681           | 0.572           | 2.72            |                 |
| TPS      | 10×10             | 0.640      | -          | -               | 0.652           | 1.86            |                 |
|          | 4×4               | 0.613      | 0.649      | 0.703           | 0.620           | 1.15            |                 |
|          | 3×3               | 0.605      | 0.649      | 0.696           | 0.614           | 1.47            |                 |
|          | 2×2               | 0.601      | 0.652      | 0.691           | 0.610           | 1.40            |                 |
|          | 1×1               | 0.600      | 0.659      | 0.69            | 0.599           | -0.01           |                 |
| MC       | 10×10             | 0.650      | -          | -               | 0.655           | 0.81            |                 |
|          | 4×4               | 0.601      | 0.638      | 0.691           | 0.605           | 0.71            |                 |
|          | 3×3               | 0.594      | 0.639      | 0.684           | 0.597           | 0.50            |                 |
|          | 2×2               | 0.595      | 0.647      | 0.685           | 0.606           | 1.73            |                 |
|          | 1×1               | 0.588      | 0.649      | 0.678           | 0.592           | 0.73            |                 |

$^a$ quality index proposed by Sauer

$^b$ quality index proposed by Palmans

$^c$ Measurement using ionization chamber CC13
Table 1 showed the result of $\text{TPR}_{20,10}$ at $10 \times 10$, $4 \times 4$, $3 \times 3$, $2 \times 2$, and $1 \times 1 \text{ cm}^2$ from both measurement, TPS calculation, and MC simulation. Our FFF LINAC had a stable beam quality for $10 \times 10 \text{ cm}^2$ around $0.643 \pm 0.006$. The $\text{TPR}_{20,10}(S)$ of small fields was varied with an average ratio compared to conventional field by 0.93 or the quality index was decreased about 7%. However, we obtained that the empirical formula in which convert PDD$_{20,10}$ to $\text{TPR}_{20,10}$ was agreed within 3% for any field sizes compared to the direct procedure of $\text{TPR}_{20,10}$. The average of $\text{TPR}_{20,10}(S)$ difference between SSD and SDD technique was 0.83% (-1.31 to 2.72%) for all modalities.

It can be seen from Table 1 that quality index described by Palmans had an overestimate calculation in order to reach the $\text{TPR}_{20,10}(10)$ from small field exposure. On the other hand, $\text{TPR}_{20,10}(10)$ in which derived from $\text{TPR}_{20,10}(S)$ of small field by Sauer showed a good equality to conventional reference. The average percentage difference were -0.23, 1.41, and 0.64% for measurement, TPS, and MC simulation, respectively. This result was obtain from the $\text{TPR}_{20,10}(S)$ empirical formula of PDD$_{20,10}$ to $\text{TPR}_{20,10}$. A similar results was found for direct $\text{TPR}_{20,10}(S)$ measurement set-up. The average $\text{TPR}_{20,10}(10)$ difference of regular and small field for CC13 measurement, TPS calculation, and MC simulation in this set-up were 0.41, 0.83, -1.09%, respectively.

Another beam characteristics in which we observed was lateral distribution especially the penumbra at small fields. The dose difference between measurement, TPS, and MC was displayed in Figure 1. The filled marker is MC to Measurement and the dash line is MC to TPS deviation. Visually, the deviation tend to zero along the lateral beam with increasing field size for MC to measurement disparity. Figure 1 displayed that the dose difference at penumbra region was near 10% in which agreed with IAEA TRS 430 for dose calculation [20] except at $1 \times 1$ and $2 \times 2 \text{ cm}^2$ of MC to TPS deviation. The maximum dose difference at $1 \times 1$ and $2 \times 2 \text{ cm}^2$ penumbra was 20.73 and 12.31%, respectively. This results was affected by the extrapolation method of TPS algorithm which the beam data of at $1 \times 1 \text{ cm}^2$ was not inputted to TPS beam configuration.

Furthermore, the photon characteristics evaluation of FFF small field beam was OFs. We did the small field OFs comparative study of CC13, PTW-31016, Gafchormic EBT3, TPS calculation, and MC simulation which shown in Figure 2. The OFs of PTW-31016 was overlap to the range of MC simulation data at all the field sizes. CC13 ionization chamber was also good for $4 \times 4$ and $3 \times 3 \text{ cm}^2$, however the discrepancy results of CC13 at $2 \times 2$ and $1 \times 1 \text{ cm}^2$ were 3.12 and 3.44%, respectively. After beam modeling, we did the TPS OFs calculation by comparing dose/MU at corresponded depth and field sizes.

![Figure 1](image.png)

**Figure 1.** Percentage dose difference on 6MV FFF lateral small field beam profile
The results showed that TPS OFs had a 1.04 ratio lower than MC simulation. Moreover, the Gafchromic EBT3 film which had a tissue equivalent and small spatial resolution achieved up to 8.84% difference to MC simulation.

4. Conclusion
This work presents an evaluation of 6 MV FFF LINAC small field beam quality and output factors by using ion chambers, film, TPS calculation, and MC simulation. The quality index of FFF beam photon was 0.643±0.06 and it was slightly depend on the opened field size. It is necessary to measure the TPR$_{20,10}(S)$ of small field with direct SDD set-up, yet convert PDD$_{20,10}$ to TPR$_{20,10}$ was also possible. However, the lateral characteristics of FFF beam from our TPS have got a high uncertainty especially at 2×2 and 1×1 cm$^2$ which the lateral dose difference reached 12.31 and 20.73%. The OFs of TPS was about -4% difference from the MC simulation. Moreover, a high uncertainty dosimetry of Gafchromic EBT film and CC13 ionization chamber at 1×1 cm$^2$ indicated that the FFF photon beam was not well traced. It showed that our FFF LINAC could be used for small field until 2×2 cm$^2$ with care. Further study of small field dosimetry are required to ensure the FFF photon was suitable for clinical purpose.

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