Beam matching of two linear accelerators, identical model and brand

T Donmoon*, S Wattanachaiyasit, U Kaewboonperm, E Meennuch, and C Klaitong
Department of Radiotherapy, Mahavajiralongkorn Thanyaburi Hospital, Pathumtani, Thailand

*Email: tinnagorn.armrt@gmail.com

Abstract. The final goal of this work is to interchange ongoing irradiated patients between the two linear accelerators (LINACs), without re-planning if any malfunction of one machine. Having two identical LINACs, only two years apart, it is our opportunity to try using beam matching techniques. First of all, we followed the vendor’s criteria, however, these are insufficient to ensure the interchangeability of the patients. The purpose of this work is to describe further and compare measurements and parameters after the initial vendor-recommended beam matching of the two LINACs. After completion of the acceptance test and initial vendor-recommended beam quality test, several parameters were measured to confirm the level of beam matching in both LINACs. The measurement consisted of specific point dose (output factors, head scatter factors, and wedge transmission factors), percentage depth dose, and beam profile. All beam matching parameters from our two LINACs are comparable and acceptable value approximate ±1% or less for both photon and electron beams; therefore, it is possible to interchange accelerators for ongoing irradiated patients without re-planning for dosimetric data as part of the treatment planning system. However, these parameters should be frequently measured/re-checked and compared between LINACs in a part of hospital quality assurance programs. Additional, the safest and most practical way to ensure that two accelerators are within acceptable clinical accuracy is to include treatment planning system (TPS) calculations in the evaluation.
1. Introduction
Radiotherapy centers with more than one LINAC of the same make, model and multileaf collimator (MLC) often desire "beam matching" for the immediate interchange of patients between these accelerators, without having to replan, if one machine is not functioning properly. A high level of similarity between beam profiles, depth dose curves and other properties from two identical LINACs signifies beam matching. Beam matching can be defined as a methodology that needs to be performed between two or more LINACs to ensure the equivalence of dose delivery. A LINAC is characterized by numerous electrical, mechanical, and dosimetric parameters. Proper evaluation of the dosimetric and the mechanical parameters is crucial for precision and accuracy in treatment delivery to patients. Some parameters relating to dose include the output factor, depth dose, beam profile, energy, and dose rate. Electromechanical parameters consist of the gantry, collimator, couch isocenters, MLC positional accuracy, MLC speed, jaw positional accuracy, and gantry speed, etc. [1, 2].

Elekta's factory matching for the photon beam requires percentage depth dose (PDD$_{10}$) to be within ±1% for the group of the beam-matched LINACs. Then, for beam profiles of 10×10 cm$^2$ and 30×30 cm$^2$ field sizes at 10 cm depth, any averaged point dose (average of the measurements over 1 cm range from that point) within the region covering 80% of full width at half maximum (FWHM) shall be within a 2% difference when compared to the same points from beam profiles of other beam-matched LINACs. Beam-matched LINACs have almost the same dosimetric characteristics and can be represented as one set of beam parameters in the treatment planning system (TPS). Having beam-matched LINACs can not only increase the flexibility in patient treatment but also reduce the social and economic effects caused by machine downtime [1, 3-4].

Currently, our center has two LINACs, identical models and brands (Elekta). Both are capable of IMRT and VMAT. The first one has been installed and working since 2016 and the second one is recently and completed installed in July 2018. Our final goal is to interchange ongoing irradiated patients between the two LINACs, without re-planning if any malfunction of one machine. Having two identical LINACs, only two years apart, it is our opportunity to try using beam matching techniques, initial experience in Thailand. First of all, we followed the vendor's criteria (photon beam quality, electron beam quality, and wedge transmission factor matching) for general beam quality tests; however, these are insufficient to ensure the interchangeability of the patients [3, 5-7]. The purpose of this work is to describe further and compare measurements and parameters after the initial vendor-recommended beam matching of the two LINACs, identical models and brands.

2. Materials and methods
2.1 Materials
Each LINAC is Elekta Infinity with agility head (80 MLC leaf pairs of 5 mm leaf width), XVI cone-beam CT and iView GT™ portal imaging. The desktop software is Integrity 3.2. The LINAC has two-photon beams of nominal energies 6 and 10 MV and five electron beams with nominal energies 6, 9, 12, 15 and 18 MeV. All measuring equipment are shown in table 1.

2.2 Methods
The measurement consisted of specific point dose (output factors), percentage depth dose and beam profiles (flatness and symmetry of both in-plane and cross-plane beam profiles) measurements, as shown in table 1. Measurement for output factor of specific field size was repeated five times to evaluate the consistency of MU delivery and detector measurements. The photon beams of the original LINAC (LINAC1) were selected as the reference for tuning of beams of the newer LINAC (LINAC2). Acceptance criteria, the difference in PDD$_{10}$ and wedge factors among matched LINACs should be within ±1%. As for flatness and symmetry of beam profiles, instead of using averaged point dose, any point dose within the 80% of the FWHM region shall be within ±2% difference window. During beam matching, all beams commissioning measurements were performed for matched photon energies.
Table 1. Measurements carried out for photons and electrons.

| Measurements                  | Equipment                                                                 | Geometry                          |
|-------------------------------|---------------------------------------------------------------------------|-----------------------------------|
| **Photons**                   |                                                                           | TSD (cm) | Depth (cm) | FS/Applicator for electron (cm²) | 2, 3, 4, 5, 10, 15,20, 30, 40 |
| Output factors in water       | Waterproof farmer chamber 30013 and micro-diamond, Unidos webline         | 90       | 10         |                               | 5, 10, 15, 20, 30 |
|                               | electrometer, Doseview™ 1D water tank                                      |          |            |                               |                     |
| 60⁰ Wedge factors             | Waterproof farmer chamber 30013,                                         | 90       | 10         |                               | 5, 10, 15, 20, 30 |
|                               | Unidos webline electrometer,                                              |          |            |                               |                     |
|                               | Doseview™ 1D water tank                                                   |          |            |                               |                     |
| Head scatter factors (HSc)    | Farmer chamber 0.6 cc with brass buildup cap, Unidos webline, in air     | 99.35/   | Brassᵃ:    | 5, 10, 15, 20, 30             |                     |
|                               | measurements                                                              | 99.25    | 0.65/0.7   | for 5 for 6/10 MV             |                     |
|                               |                                                                          | 6/10     | 6/10       | MV                           |                     |
| Depth dose                    | Semiflex 3D ion chamber, PTW beam scan, Mephysto v. 3.3                  | 90       | -          | 5, 10, 15, 20, 30             |                     |
| In-plane and cross-plane profiles | Diode P, PTW beam scan, Mephysto v. 3.3                                      | 90       | 10         |                               |                     |
| **Electron**                  |                                                                           |          |            |                               |                     |
| Output factors in water       | Roos ionization chamber, Unidos webline electrometer, Doseview™          | 100      | -          | Zref                         | 6,10, 14, 20 |
|                               | 1D water tank                                                             |          |            |                               |                     |
| Depth dose                    | Semiflex 3D ion chamber, PTW beam scan, Mephysto v. 3.3                  | 100      | -          | 6,10, 14, 20                  |                     |
| In-plane and cross-plane profiles | Semiflex 3D ion chamber, PTW beam scan, Mephysto v. 3.3                  | 100      | -          | R₈₀/₂                         | 6, 20               |

ᵃ Effective point of measurement at the isocenter, brass build-up cap difference for 6 and 10 MV.

3. Results

3.1. Photons

For both 6 and 10 MV photon beams, the output factors, head scatter factors, and wedge transmission factors measured on both LINACs were comparable. The difference of output factors between two LINACs for all field sizes had an agreement about ±1%, as shown in table 2. The maximum difference in output factors were 0.5% and 1.3%, which were the difference in output factors of 40×40 cm² and 3×3 cm² field size of 6 and 10 MV, respectively. A total of twenty photon beam profiles of the newer LINAC was taken to compare with reference beams from the original LINAC. Fourteen beam profiles were below 1%, and six beam profiles were between 1% and 2%. For the percentage depth dose, all curves were compared with a deviation of less than 1%.

For depth dose; parameter used for the beam quality specification with typical values for clinical megavoltage photon beams were the depth of dose maximum (dmax) or R₁₀₀ and Tissue Phantom Ratio (TPR₂₀,₁₀). The results were tabulated in Table 3 and 4.
### Table 2. Output factors for photon beams.

| Field size (cm²) | Output factor of 6 MV | Difference (%) | Output factor of 10 MV | Difference (%) |
|------------------|-----------------------|----------------|------------------------|----------------|
|                  | LINAC1 | LINAC2 | LINAC1 | LINAC2 | LINAC1 | LINAC2 | LINAC1 | LINAC2 | LINAC1 | LINAC2 | LINAC1 | LINAC2 |
| 2x2              | 0.8103 | 0.8090 | 0.1607 | 0.8090 | 0.8154 | 0.7849 |
| 3x3              | 0.8479 | 0.8469 | 0.1181 | 0.8538 | 0.8652 | 1.3179 |
| 4x4              | 0.8786 | 0.8768 | 0.2053 | 0.8865 | 0.8953 | 0.9829 |
| 5x5              | 0.9059 | 0.9047 | 0.1326 | 0.9115 | 0.9194 | 0.8593 |
| 10x10            | 1.0000 | 1.0000 | 0.0000 | 1.0000 | 1.0000 | 0.0000 |
| 15x15            | 1.0579 | 1.0601 | 0.2075 | 1.0490 | 1.0478 | 0.1145 |
| 20x20            | 1.0967 | 1.0979 | 0.1093 | 1.0813 | 1.0777 | 0.3340 |
| 30x30            | 1.1434 | 1.1457 | 0.2008 | 1.1201 | 1.1128 | 0.6560 |
| 40x40            | 1.1612 | 1.1665 | 0.4544 | 1.1343 | 1.1277 | 0.5853 |

### Table 3. Energy match analysis.

| Energy (MV) | TPR<sub>20,10</sub> | Difference (%) |
|-------------|---------------------|----------------|
|             | LINAC1 | LINAC2 |                |
| 6           | 0.6790 | 0.6766 | 0.35           |
| 10          | 0.7272 | 0.7243 | 0.40           |

### Table 4. Depth dose analysis.

| Field size (cm²) | Energy (MV) | d<sub>max</sub> (mm) | Difference (mm) |
|------------------|-------------|-----------------------|-----------------|
|                  |             | LINAC1 | LINAC2 | LINAC1 | LINAC2 | LINAC1 | LINAC2 | LINAC1 | LINAC2 | LINAC1 | LINAC2 |
| 5x5              | 6           | 15.00 | 16.00 | 1.00 |
|                  | 10          | 23.00 | 22.00 | 1.00 |
| 10x10            | 6           | 15.00 | 16.00 | 1.00 |
|                  | 10          | 22.00 | 21.40 | 0.60 |
| 15x15            | 6           | 15.00 | 14.40 | 0.60 |
|                  | 10          | 20.00 | 20.00 | 0.00 |
| 20x20            | 6           | 14.00 | 14.30 | 0.30 |
|                  | 10          | 19.00 | 19.00 | 0.00 |
| 30x30            | 6           | 13.00 | 13.90 | 0.90 |
|                  | 10          | 17.00 | 17.90 | 0.90 |

#### 3.2. Electrons

Output factors for all energies overall applicator sizes were within ±1%, as shown in table 5. The largest deviation of the output factor between the two LINACs was about 0.7%. For the percentage depth dose, twenty curves were compared with a deviation of less than 1%. The maximum deviation was 0.07 cm for all electron energies and applicators when comparing the depth of the 50% dose (R<sub>50</sub>), as shown in table 6.
### Table 5. Output factors for electron beams.

| Applicator size (cm²) | Electron energy (MeV) | Output factor | Difference (%) |
|-----------------------|-----------------------|---------------|----------------|
|                       | LINAC1                | LINAC2        |                |
| 6×6                   | 6                     | 0.8573        | 0.8511         | 0.7285         |
|                       | 9                     | 0.9328        | 0.9373         | 0.4801         |
|                       | 12                    | 0.9680        | 0.9659         | 0.2174         |
|                       | 15                    | 0.9727        | 0.9754         | 0.2768         |
|                       | 18                    | 0.9842        | 0.9885         | 0.4350         |
| 10×10                 | 6                     | 0.9727        | 0.965          | 0.7979         |
|                       | 9                     | 1.0109        | 1.0115         | 0.0593         |
|                       | 12                    | 1.0111        | 1.005          | 0.6070         |
|                       | 15                    | 1.0100        | 1.0098         | 0.0198         |
|                       | 18                    | 1.0004        | 1.0042         | 0.3784         |
| 14×14                 | 6                     | 0.9967        | 0.9966         | 0.0100         |
|                       | 9                     | 0.9982        | 0.9985         | 0.0300         |
|                       | 12                    | 0.9998        | 0.9971         | 0.2708         |
|                       | 15                    | 0.9914        | 0.9933         | 0.1913         |
|                       | 18                    | 0.9851        | 0.9895         | 0.4447         |
| 20×20                 | 6                     | 2.46          | 2.45           | 0.03           |
|                       | 9                     | 3.61          | 3.59           | 0.02           |
|                       | 12                    | 4.74          | 4.76           | 0.02           |
|                       | 15                    | 5.92          | 5.97           | 0.05           |
|                       | 18                    | 6.99          | 7.01           | 0.02           |
|                       | 10×10                 | 6             | 2.46          | 2.45           | 0.01           |
|                       | 9                     | 3.60          | 3.61           | 0.01           |
|                       | 12                    | 4.74          | 4.76           | 0.02           |
|                       | 15                    | 5.96          | 6.02           | 0.06           |
|                       | 18                    | 7.12          | 7.14           | 0.02           |
| 14×14                 | 6                     | 2.45          | 2.45           | 0.00           |
|                       | 9                     | 3.60          | 3.62           | 0.02           |
|                       | 12                    | 4.74          | 4.76           | 0.02           |
|                       | 15                    | 5.97          | 6.04           | 0.07           |
|                       | 18                    | 7.14          | 7.17           | 0.03           |
| 20×20                 | 6                     | 2.45          | 2.45           | 0.00           |
|                       | 9                     | 3.59          | 3.60           | 0.01           |
|                       | 12                    | 4.74          | 4.76           | 0.02           |
|                       | 15                    | 5.96          | 6.02           | 0.06           |
|                       | 18                    | 7.15          | 7.17           | 0.02           |

### Table 6. The difference in $R_{50}$ for electron beams.

| Applicator size (cm²) | Electron energy (MeV) | $R_{50}$ (cm) | Difference (cm) |
|-----------------------|-----------------------|---------------|-----------------|
|                       |                       | LINAC1        | LINAC2          |                |
| 6×6                   | 6                     | 2.48          | 2.45            | 0.03           |
|                       | 9                     | 3.61          | 3.59            | 0.02           |
|                       | 12                    | 4.74          | 4.76            | 0.02           |
|                       | 15                    | 5.92          | 5.97            | 0.05           |
|                       | 18                    | 6.99          | 7.01            | 0.02           |
| 10×10                 | 6                     | 2.46          | 2.45            | 0.01           |
|                       | 9                     | 3.60          | 3.61            | 0.01           |
|                       | 12                    | 4.74          | 4.76            | 0.02           |
|                       | 15                    | 5.96          | 6.02            | 0.06           |
|                       | 18                    | 7.12          | 7.14            | 0.02           |
| 14×14                 | 6                     | 2.45          | 2.45            | 0.00           |
|                       | 9                     | 3.60          | 3.62            | 0.02           |
|                       | 12                    | 4.74          | 4.76            | 0.02           |
|                       | 15                    | 5.97          | 6.04            | 0.07           |
|                       | 18                    | 7.14          | 7.17            | 0.03           |
| 20×20                 | 6                     | 2.45          | 2.45            | 0.00           |
|                       | 9                     | 3.59          | 3.60            | 0.01           |
|                       | 12                    | 4.74          | 4.76            | 0.02           |
|                       | 15                    | 5.96          | 6.02            | 0.06           |
|                       | 18                    | 7.15          | 7.17            | 0.02           |
4. Discussion and Conclusion

In this work, a methodology has been developed for the quantitative evaluation of beam matching between two LINACs and demonstrated for the Elekta machines. The measurements for output factor, percentage depth doses and beam profiles of photon beams were performed using a 30013 (0.6 cc) ion chamber, semiflex 3D ion chamber, and diode P, respectively. The chambers were offset to the effective point of measurement at 0.5 cm (1.2 mm for a 30013 ion chamber) for all measurements as per the IEC standard. For electron beam profiles, the depth of measurement for electron 6 MeV was the depth of maximum absorbed dose, 13 mm. The depths of electron 9, 12, 15 and 18 MeV were half the depth of the specified penetrative quality of 80% the maximum absorbed dose (R_{100}). The depths consisted of 15, 20, 25 and 30 mm for 9, 12, 15 and 18 MeV, respectively.

As shown in Table 2 and 5, the difference of output factors between two LINACs for all photon and electron energies had an agreement about ±1%. Moreover, the head scatter factors and wedge transmission factors, the results showed that the difference between two LINACs for all field sizes of all photon energies were within ±2%.

An analysis of PDD data was performed to evaluate the energy match. The d_{max} of all photon energies were evaluated for field size 10×10 cm². The energy parameter, TPR_{20,10} values of all photon energies were obtained. As shown in Table 3, the difference of TPR_{20,10} between two LINACs was within ±1%. For d_{max}, the difference between two LINACs was within ±1%, as shown in Table 4. The results showed that no energies difference.

All beam matching parameters from our two identical linear accelerators, two years apart, are comparable and maybe acceptable about ±1% or less for both photon and electron beams; therefore, it is possible to interchange accelerators for ongoing irradiated patients without re-planning for dosimetric data as part of the treatment planning system. However, these parameters should be frequently measured/re-checked and compared between accelerators in a part of hospital quality assurance programs, especially when interchange occurs. To ensure a satisfactory beam match the dose prediction must be adopted in the beam matching procedure. Further, the comparison between measurements and calculations should be done in absolute dose terms.

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