Evaluation of MU2net as an online secondary dose check for MR guided radiation therapy with the Elekta unity MR linac

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Abstract
During the adaptive workflow associated with MRgRT, a secondary dose calculation is required and MU2net (DOSIsoft, France) is one commercial option. The suitability of MU2net to be used in conjunction with the online Monaco treatment planning system of the Elekta Unity (Elekta AB, Stockholm, Sweden), is evaluated in this work. Monaco and MU2net point doses are compared for various fields on and off axis and at different SSDs. To investigate the comparative effects of attenuation due to the cryostat, couch and posterior coil, measured, MU2net and Monaco dose outputs at the isocentre, as a function of gantry angle, were compared. Point doses for the beams of nine step and shoot IMRT (SSIMRT) test plans (courtesy Elekta) were calculated with Monaco v5.4 and compared to corresponding doses computed with MU2net. In addition, Monaco v5.4 and MU2net point doses were compared for 1552 beams treated on the Unity at our facility. For the on-axis fields investigated the agreement between MU2net and measured data is acceptable. MU2net and Monaco point doses for the Elekta SSIMRT test plans were within ± 5.0% and ± 6.4% for beams delivered from gantry zero and at planned beam angles, respectively. For the 1552 beams delivered approximately 80.0% of MU2net and Monaco point doses agree within ± 5.0%, therefore it is recommended to correlate MU2net Dose Reference Points (DRPs) with pre and post treatment dosimetry verification. Computational accuracy of MU2net could be enhanced with improved modelling of attenuation due to the couch, cryostat and posterior MR imaging coil.

Keywords Secondary dose calculation · Elekta unity · MR-Linac · MU2net

Introduction
In December 2019 the Townsville University Hospital Cancer Centre introduced an Elekta Unity MR-linac (Elekta AB, Stockholm, Sweden) to clinical use, the first such cancer treatment system in the southern hemisphere. This linac combines radiation therapy with high soft-tissue contrast MR imaging and facilitates adaptive radiotherapy using real time Graphical Processing Unit (GPU) based Monte Carlo treatment planning (Monaco v5.4) [1–4]. The Monte Carlo dose calculation algorithm (GPUMCD) incorporates radiation transport in the presence of a magnetic field and makes use of GPUs, facilitating parallel processing which reduces calculation times [5].

The MR linac basic structure in Fig. 1 consists of a beam generation system that is mounted on a vertically orientated rotating annulus. The annulus rotates at 6.0 rpm delivering a 7 MV FFF beam directed to the centre of rotation within the bore of the Unity. A modified Ingenia 1.5 T superconducting magnet is mounted such that each of its two superconducting coils sit on either side of the rotating annulus. The magnet cryostat containing liquid helium is located within the annulus (see Fig. 1) and radiation beams must traverse the cryostat before entering the bore. Consequently the angular dependence of the cryostat attenuation needs to be characterised and modelled in the treatment planning system [6]. With this configuration B₀ is perpendicular to
the axis of rotation of the x-ray source for all beam directions [7]. The source to isocentre distance is 143.5 cm, the bore diameter is 70.0 cm and the couch is 14.0 cm below the isocentre. There is no collimator rotation and the maximum field size in the isocentric plane is 57.4 cm crossplane, (IEC61217 x-direction) and 22.0 cm inplane, (IEC61217 y-direction). The multileaf collimator is based on the Elekta Agility model with 80.0 leaf pairs with rounded leaf ends, each with a projected width of approximately 7.18 mm at isocentre. Leaf motion occurs parallel to the y-axis which is also the only direction of motion for the couch. Since the couch direction of movement is perpendicular to the plane of rotation of the x-ray source, only coplanar treatments are possible and the current treatment options are conformal fields and step and shoot IMRT.

The adaptive treatment planning options available with Monaco are broadly divided into two main workflows, namely Adapt to Position (ATP) and Adapt to Shape (ATS). For further details of both ATP and ATS the reader can refer to Winkel et al. [8]. With adaptive planning, it is critical to have an independent online dosimetric evaluation of each adapted plan, a secondary MU/dose check, before proceeding to treat. For the clinical cases considered in this work ATP was exclusively used.

At our facility we evaluated the use of MU2net v2.1.1.7 (DOSIsoft, France) for monitor unit (MU) verification with the Elekta Unity MR linac. The commissioning of this dose calculation engine is based on MPPG5a [9] recommended tests and is the subject of an internal report. In this work we report on output factors for on axis square fields and off-axis customised fields, the variation of output with gantry angle and treatment plan point dose comparisons between MU2net and Monaco v5.4.

The dose computation in MU2net is divided into two successive steps: reconstruction of the beam fluence at the exit of the treatment head and dose computation in the medium [10]. The beam fluence map is reconstructed according to the imported DICOM RT Plan data. For each irradiation segment, i.e. between two successive control points (CPs), the calculation considers the open FFF beam profile modified by the leaf arrangement. It takes into account the respective leaf/jaw transmission factor and the leaf penumbra shape by applying a gaussian filter. The fluence map is expressed in terms of MU given from the RT Plan file for each irradiation segment. This MU data is corrected for head-scatter effects ($S_c$ component) to report the variations of the dose rate with the beam aperture. The total fluence map is reconstructed from the whole set of CPs and this representation of the beam intensity modulation is applied onto a large parallelepiped water phantom for dose calculation. The dose engine separates a primary dose calculation considering a simple exponential attenuation function of the radiological depth, and a scatter dose reconstructed with a Clarkson’s sector summation algorithm [10]. When imported into MU2net, DICOM RT Structure Set files are used to extract radiological depths from a reconstructed anatomical patient model aligned on the treatment couch. MU2net is a dose point comparison solution, designed for fast computation time and ease of implementation. In practice MU2net point dose comparisons with Monaco are achieved by assigning DRPs to each beam of a Monaco plan and exporting the Monaco plan (Structure Set and Total Plan) to MU2net. MU2net is a dose point comparison solution, designed for fast computation time and ease of implementation. In practice MU2net point dose comparisons with Monaco are achieved by assigning DRPs to each beam of a Monaco plan and exporting the Monaco plan (Structure Set and Total Plan) to MU2net. MU2net is accessed via a web-based interface and resides on a virtual server (16.0 MB CPU). Once accessed, MU2net launches the dose computation at the DRPs for each beam and compares them automatically to corresponding TPS point doses. A single DRP can be selected for all beams but generally individual DRPs for each beam is preferable. It should be noted that Monaco exports point dose DRP values to MU2net. However, for comparison of corresponding DRPs, the mean dose within a sphere of radius 3.0 mm for each Monaco DRP has been used in this work. MU2net is only a verification system for point doses, it

Fig. 1 MR Linac: a accelerating waveguide, b rotating gantry, c cryostat, d gradient coils, superconducting coils and system body coil (QBC), e active shielding coils, f EPID, g beam stopper (courtesy of Elekta)
cannot be used like a conventional TPS. An alternative comparable secondary MU check, RadCalc (Lifeline Software Inc., Tyler, USA), is described by Graves et al. [11].

Our department has successfully introduced MU2net as a secondary dose check. To the best of our knowledge this is the first report dedicated to the use of this software in the adaptive planning workflow of an Elekta Unity system.

**Materials and methods**

**Model configuration**

The MU2net dose engine is modelled using depth dose, output factors and profiles for the 7 MV FFF photon beam of the Unity, in a B = 0 T environment (courtesy Elekta, Crawley, UK). The output of the Elekta Unity in our department is set to 1.000 Gy / 100 MU (B = 1.5 T) at the isocentre, depth of 5.0 cm in water, SSD = 138.5 cm, gantry 90.0°, for a 10.0 × 10.0 cm² field. These are also the conditions associated with the calibration point for Monaco. The dose is calibrated at gantry 90.0°, due to the constant helium fill in this direction. At a depth of 10.0 cm, gantry 0.0°, the specified dose calibration point for MU2net, the calculated output is 0.862 Gy / 100 MU.

**Output factors**

Measured square field output factors were compared to calculated values for MU2net and Monaco for field sizes ranging from 1.0 × 1.0 cm² to 22.0 × 22.0 cm². Measurements on the Unity were performed as part of the Elekta beam data collection work using a MicroDiamond detector (PTW60019 S/N: 123,297) and Semiflex (PTW31010 S/N: 007,799) ionization chamber, PTW UNIDOS electrometer (Webline S/N: 00,017, firmware v2.06 S/N: 2172) and an Elekta supplied water tank (PTW Beamscan MR S/N: 181,208). The MicroDiamond detector was used for fields ≤ 10.0 × 10.0 cm² and the Semiflex was used for fields ≥ 5.0 × 5.0 cm². Measurement points were positioned on the central axis at a depth of 5.0 cm, SSDs of 133.5 cm and 138.5 cm. Each chamber was centred at its EPOM along the z direction and offset 1 mm to patient left to account for the Lorentz force. For the 1.0 × 1.0 cm² and 2.0 × 2.0 cm² fields the relevant field dependent chamber correction factors from TRS483 [12] (0.984 and 0.997 respectively) were applied to the measured data. The TRS483 factors are obtained for conventional linear accelerator measurement conditions. As such, our measurements differ with respect to the presence of the magnetic field and larger SSD. For output factors, the larger SSD should have little-to-no impact. We have not performed these measurements in a B = 0 T environment on the MR Linac and therefore do not have quantitative comparison on the uncertainty of the Lorentz shift with and without the magnetic field.

In addition, EBT3 film (Ashland ISP Advanced Materials, NJ, USA) was used to determine output factors at both depths for field sizes ≤ 10.0 × 10.0 cm². Due to the inability to vary couch height, film depth was altered by varying solid water phantom slabs at depths of 133.5 cm and 138.5 cm SSD were achieved with 10 cm and 14 cm height stack. The film was centred on central axis by using an inhouse designed aluminium ruler, which was centred on the RW3 slab phantom at the desired measurement depth. An EPID image was captured (Field size: 22.0 × 22.0 cm², 20 MU) to check the ruler and central cross hair alignment. The slab was shifted until the centre of the ruler was aligned with the cross hair (Fig. 2). The film was placed on the centre of the slab phantom block and exposed to 100 MU with four calibration films 0 MU, 50 MU, 100 MU and 200 MU. The films were digitized to a TIFF format with an RGB flatbed scanner (EPSON Expression 10000XL) at 72 dpi, in transmission mode, with no colour or sharpness correction and consistent orientation. The digitized film was then converted to dose maps using FilmQA™ Pro (Ashland ISP Advanced Materials, NJ, USA) using a triple channel analysis [13].

**Directional dependence**

Due to the non-uniform attenuation of the cryostat there is a corresponding output variation with gantry angle and this was quantified by Elekta as part of their pre-clinical testing (Fig. 4, data courtesy of Elekta). The measurements were performed using a Farmer chamber (PTW30013 S/N:
010,499) and PTW UNIDOS electrometer (Webline S/N: 2172) placed in a cylindrical phantom on central axis. During these measurements the posterior coil was removed [7]. In addition, the transmission and associated attenuation of the treatment beam through the couch and posterior coil (located beneath the couch) is dependent on the gantry angle (for gantry angles 120.0° – 240.0° the beam transits the couch). The various attenuation processes together with any machine related output fluctuations determine the net variation in output with gantry angle at the isocentre. In order to determine this variation, measurements were performed using a Farmer chamber (PTW30013 S/N: 011,298) and PTW UNIDOS electrometer (Webline S/N: 00,017), with the chamber centred in a 6.0 cm diameter water filled cylindrical phantom (Fig. 3). Using the EPID the long axis of the cylinder/chamber was aligned parallel to the y-axis, 14.0 cm above the couch, and with the chamber reference point at the isocenter. The cylindrical chamber holder, developed on site, can be rotated in 15.0° increments and maintains the same orientation with respect to the beam as the gantry is rotated by the same angle. Chamber measurements for 100 MU and a field size of 5.0 × 5.0 cm² were recorded every 15.0° for gantry angles ranging from 0.0° to 345.0°, avoiding the cryostat pipe at 13.0° that connects the split superconducting B₀ coils. Measured output values at each angle were normalized to the G90 value.

A model of the cylindrical phantom (Relative Electron Density (RED = 1.000) was developed in Monaco and the dose was determined at the phantom centre for the same field size and range of gantry angles as described above. Monaco calculations include attenuation contributions for the cryostat, couch and posterior coil. For each gantry angle, corresponding Monaco plans were exported to MU2net and dose is calculated. It is important to note that the cryostat and posterior coil do not feature in the MU2net computations. However, in Monaco the cryostat attenuation is accounted for by applying an angular dependent output correction determined by Elekta (Fig. 4). In the current version of Monaco, the coil can be visualized but cannot be exported as the coil is not defined as a contour structure, however it is included in dosimetric calculations (RED = 0.181). To estimate the dosimetric effect of including the posterior coil in the MU2net dose computation, a separate structure was contoured over the posterior coil. This structure, layered above the couch structures, was assigned the RED of the posterior coil and was exported to MU2net, during the testing phase as this cannot be done during the clinical workflow.

Additionally, the effect of not including the posterior coil in Monaco was investigated. Here the contoured coil structure was assigned a RED of 0.010, effectively rendering the coil radiotransparent. This structure was also exported to MU2net. The angular dependence of the central axis dose calculated using MU2net with the contoured and radiotransparent coil structure was determined.

Fig. 3 Directional dependence set up; in house designed phantom with Farmer Chamber inside

Fig. 4 Relative cryostat transmission characterisation curve, normalized to G90 (courtesy of Elekta)
Custom fields

During Elekta data collection, a selection of central axis square field output factors are measured using the Elekta supplied water tank for the purpose of beam modelling. In addition, measurements for customer defined fields were performed at gantry 0.0°, referred to as custom fields in this work. These fields consisted of rectangular fields 14.0 × 4.0 cm² and 4.0 × 14.0 cm² and 5.0 × 5.0 cm² square fields (Fig. 5). Custom fields 4.0 × 14.0 cm² were centred on axis at X = ± 24.0 cm, ± 12.0 cm and 0.0 cm. Similarly, 14.0 × 4.0 cm² were centrally located at Y = ± 7.0 cm and X = Y = 0.0 cm. For each of these fields, measurements were performed at three locations, shown in Fig. 5. In addition, 5.0 × 5.0 cm² fields were centred (X, Y) at (−18.0 cm, ± 4.0 cm) and (18.0 cm, ± 4.0 cm) and X = Y = 0. All the above custom fields were selected to attempt to cover a large area of the maximum collimator opening. For each field, charge readings at 10.0 cm depth, SSD = 133.5 cm, 200 MU were obtained using a PTW MicroDiamond detector and a PTW UNIDOS electrometer. Readings were normalized to that of a 10.0 × 10.0 cm² field to determine output factors.

Monaco DRPs for custom fields were computed using a phantom (54.5 cm × 30.0 cm × 24.0 cm, forced RED = 1.000) to match the water tank dimensions during data acquisition. Dose calculations for 200 MU, SSD 133.5 cm, gantry angle 0.0° and depth 10.0 cm were obtained for each field. The beam exclusion zone included in the current clinical beam model, accounts for a larger cryostat pipe and disables dose calculation for a 4.0 × 14.0 cm² field at X = 24.0 cm. To overcome this, in the beam model, the ‘parm’ file, which describes the exclusion zone, was temporarily swapped to enable the calculation for this measurement.

Sample Elekta plans – dose reference point evaluation

As part of the Elekta beam validation process, nine step and shoot IMRT plans were calculated in Monaco on a phantom (30.0 cm × 30.0 cm × 19.0 cm, forced RED = 1.000). These plans were also used to compare Monaco and MU2net calculated dose for selected DRPs. Each DRP was calculated with either all gantry angles set to zero (perpendicularly) or with planned treatment angles (compositely) using a 30.0 cm × 30.0 cm × 17.8 cm phantom, (forced RED = 1.000). The Monaco dose for each plan was calculated with a grid spacing of 0.2 cm and a statistical uncertainty of 3.0% per control point. Each plan with phantom and couch structures was exported to MU2net and dose to the DRPs for each beam were computed.

Clinical cases

Pretreatment QA

During pretreatment QA, the reference plan from which adapted plans are created is verified. For this QA, fraction zero, a DRP is assigned to each beam in Monaco and dose is calculated. Broadly speaking DRPs are selected in a uniform dose region within the planning target volume (PTV). The DICOM RT Plan and RT Structure Set (couch and patient) are exported to MU2net for secondary dose computation. The computed MU2net DRP values and corresponding Monaco mean dose DRP values are copied and manually compared using Microsoft Excel. To ensure MU2net versus Monaco DRP discrepancies are less than a ±5% tolerance, the DRP is chosen in accordance with the generally accepted ICRU recommendations of a homogenous region within the specific beam [14]. In some instances, highly

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**Fig. 5** BEV of custom fields, where the dot (·) represents the chamber measurement position
modulated plans with small fields, heterogeneities and non-uniformity can require reselection of DRP. However if this could not be achieved and the DRP discrepancy was then taken as a baseline for that beam during the adaptive planning process. For such beams ±5.0% discrepancies from the baseline value were used during the online independent MU checking procedure. Following the reference plan and the identification of baseline discrepancies for the DRPs for all beams, our procedure is to complete plan QA using either EBT3 (maximum dose < 10.0 Gy) or EBT XD (maximum dose > 10.0 Gy). Using FilmQA Pro and triple channel dosimetry [13], gamma criteria of 2%/2 mm (global) are applied to each film-Monaco planar dose comparison.

**Treatment**

Our first patient on the Elekta Unity was treated in December 2019 and a total of 215 fractions (1552 beams) were delivered in 2020. Some of the more common treatment sites included: intact prostate, common iliac node, external iliac node, pelvic node, para-aortic node and seminal vesicles. The PTVs of these treatment sites ranged from 1.9 cm^3 to 162.4 cm^3, with field sizes varying from approximately 1.0 × 1.0 cm^2 to 8.0 × 8.0 cm^2. To observe if PTV size has an effect on the Monaco versus MU2net percentage differences, the patient data was separated into two categories: prostate (PTV > 77.0 cm^3) and “nodes/vesicles” (PTV < 21.0 cm^3). For clinical workflow purposes, average MU2net calculation times were approximately 1.0 min. On average the treatment time per patient was 45.0 min.

**Results**

**Output factors**

The variation of measured and calculated output factors for the field sizes and SSDs referred to above are shown in Figs. 6 and 7. As several means of measuring output factors were available to us, we performed those measurements and have presented them all in the figures to show a representative comparison of typical clinical methods. Numbers quoted below for discrepancies between MU2net, Monaco and measurement (Semiflex and MicroDiamond), are for the worst-case. Measured and Monaco output factors for both SSDs agreed within 1.0% for all field sizes.

At SSD 133.5 cm measured and MU2net output factors, for field sizes 1.0 × 1.0 cm^2 to 14.0 × 14.0 cm^2 are within ±1.7% and as the field size increases from 15.0 × 15.0 cm^2 to 22.0 × 22.0 cm^2 the discrepancy ranges from 2.1% to 3.5%. At SSD 138.5 cm measured and MU2net output factors, for field sizes 1.0 × 1.0 cm^2 to 15.0 × 15.0 cm^2 are within ±2.2% and for the larger field sizes 20.0 × 20.0 cm^2 to 22.0 × 22.0 cm^2 the discrepancy increases to 4.1%.

For 133.5 cm and 138.5 cm SSD, measured and EBT3 output factors for field sizes 3.0 × 3.0 cm^2 to 10.0 × 10.0 cm^2 were within ±1.4% and ±2.2% respectively and for field sizes below 2.0 × 2.0 cm^2 the maximum discrepancies are -2.7% and —2.9% respectively.

**Directional dependence**

Angular dependent normalised (G90) output values for Monaco, MU2net (with/without posterior coil) and measured data (Farmer Chamber readings) are shown in Fig. 8.
and presented in Table 1. Percentage differences for both Monaco and MU2net relative to measured data are shown in parentheses. In the current clinical workflow, MU2net computations do not include the posterior coil since the RT Structure Set exported from Monaco does not include this structure as discussed above. Absolute percentage differences between MU2net and measured data vary from 1.3 to 5.3% (mean 4.2%) at gantry angles ranging from 120.0° to 240.0°. With the inclusion of a posterior coil, in MU2net the absolute mean difference decreases to 2.4%, differences at gantry angles of 120.0° and 240.0° are unchanged. With or without the posterior coil absolute differences between MU2net and measured data vary by −0.9 to 1.8% for gantry angles 0.0° to 105.0° and 250.0° to 345.0°. For the same range of angles, percentage differences between Monaco and measured data are within ±0.2%. However, in the range of 120.0° to 240.0° Monaco output values are less than measured values with percentage differences in the range of −1.1% to −3.1% with a mean difference −1.9%.

Figure 9, displays directional dependence through the couch between measured (Farmer Chamber), Monaco, Monaco with a radiotransparent posterior coil, MU2net and MU2net + contoured posterior coil. Average differences between MU2net and measured data are decreased from 2.1 to 1.4% with the contoured coil model included. In addition, the average discrepancy for Monaco and measured data is—0.1% without the coil (RED = 0.010) compared to—1.9% with the coil. Due to the lateral extent of the coil model there is no change in the discrepancy between MU2net and measured output at 120.0° and 240.0°.
Measured MicroDiamond, MU2net and Monaco custom field output factors are shown in Table 2, percentage differences relative to measured dose are shown in parentheses. Table 2 displays the output factors for a 4.0 x 14.0 cm\(^2\) field which were shifted off axis in the ±X directions. At a field offset of X = −24.0 cm the average percentage difference between the measured and MU2net output factors is 8.4% whereas for X = 24.0 cm the difference is 11.6%. As
Table 2  Custom field output factors for measured (MicroDiamond), MU2net and Monaco

(a) Field size 4.0×14.0 cm²

| Field offset (cm) | Measurement point offset (cm) | OF Micro Diamond | OF MU2net (% difference) | OF Monaco (% difference) |
|------------------|-------------------------------|------------------|--------------------------|--------------------------|
| X                | Y                             | X                | Y                        |                          |
| −24.0            | 0.0                           | −24.0            | 0.0                      | 0.45                     | 0.48 (8.6)               | 0.43 (−4.2)              |
|                  |                                | −24.0            | 5.0                      | 0.43                     | 0.47 (8.4)               | 0.41 (−4.3)              |
|                  |                                | −24.0            | −5.0                     | 0.43                     | 0.47 (8.3)               | 0.41 (−3.8)              |
| 24.0             | 0.0                           | 24.0             | 0.0                      | 0.44                     | 0.47 (11.7)              | 0.43 (−1.2)              |
|                  |                                | 24.0             | 5.0                      | 0.42                     | 0.47 (11.7)              | 0.42 (−1.1)              |
|                  |                                | 24.0             | −5.0                     | 0.42                     | 0.47 (11.3)              | 0.42 (−1.3)              |
| −12.0            | 0.0                           | −12.0            | 0.0                      | 0.69                     | 0.71 (2.8)               | 0.68 (−2.2)              |
|                  |                                | −12.0            | 5.0                      | 0.66                     | 0.68 (2.8)               | 0.65 (−1.7)              |
|                  |                                | −12.0            | −5.0                     | 0.66                     | 0.68 (2.8)               | 0.65 (−1.8)              |
| 12.0             | 0.0                           | 12.0             | 0.0                      | 0.68                     | 0.71 (4.6)               | 0.69 (1.1)               |
|                  |                                | 12.0             | 5.0                      | 0.65                     | 0.69 (6.8)               | 0.66 (0.9)               |
|                  |                                | 12.0             | −5.0                     | 0.65                     | 0.68 (4.4)               | 0.66 (0.8)               |
| 0.0              | 0.0                           | 0.0              | 0.0                      | 0.94                     | 0.93 (−1.0)              | 0.95 (0.6)               |
|                  |                                | 0.0              | 5.0                      | 0.86                     | 0.89 (2.8)               | 0.86 (0.0)               |
|                  |                                | 0.0              | −5.0                     | 0.86                     | 0.85 (−0.3)              | 0.87 (1.2)               |

(b) Field size 14.0×4.0 cm²

| Field offset (cm) | Measurement point offset (cm) | Field offset (cm) | Measurement point Offset (cm) | OF Monaco (% difference) |
|------------------|-------------------------------|------------------|-----------------------------|--------------------------|
| X                | Y                             | X                | Y                           |                          |
| 0.0              | −7.0                          | 0.0              | −7.0                        | 0.81                     | 0.83 (1.4)               | 0.82 (0.6)               |
|                  |                                | 5.0              | −7.0                        | 0.76                     | 0.77 (1.8)               | 0.77 (1.8)               |
|                  |                                | −5.0             | −7.0                        | 0.77                     | 0.77 (1.1)               | 0.76 (−0.7)              |
| 0.0              | 7.0                           | 0.0              | 7.0                         | 0.82                     | 0.82 (0.7)               | 0.82 (0.1)               |
|                  |                                | 5.0              | 7.0                         | 0.76                     | 0.77 (1.2)               | 0.77 (1.5)               |
|                  |                                | −5.0             | 7.0                         | 0.77                     | 0.77 (0.6)               | 0.76 (−1.3)              |
| 0.0              | 0.0                           | 0.0              | 0.0                         | 0.94                     | 0.93 (−0.9)              | 0.95 (0.6)               |
|                  |                                | 5.0              | 0.0                         | 0.86                     | 0.85 (−0.2)              | 0.87 (1.6)               |
|                  |                                | −5.0             | 0.0                         | 0.86                     | 0.86 (−0.8)              | 0.86 (−0.7)              |

(c) Field size 5.0×5.0 cm²

| Field offset (cm) | Measurement point offset (cm) | Field offset (cm) | Measurement point Offset (cm) | OF Monaco (% difference) |
|------------------|-------------------------------|------------------|-----------------------------|--------------------------|
| X                | Y                             | X                | Y                           |                          |
| −18.0            | 4.0                           | −18.0            | 4.0                         | 0.53                     | 0.57 (6.6)               | 0.52 (−2.3)              |
| −18.0            | −4.0                          | −18.0            | −4.0                        | 0.53                     | 0.57 (6.6)               | 0.52 (−2.1)              |
| 18.0             | 4.0                           | 18.0             | 4.0                         | 0.52                     | 0.57 (8.9)               | 0.53 (1.2)               |
| 18.0             | −4.0                          | 18.0             | −4.0                        | 0.52                     | 0.57 (8.8)               | 0.53 (1.2)               |
| 0.0              | 0.0                           | 0.0              | 0.0                         | 0.92                     | 0.91 (−1.2)              | 0.92 (−0.1)              |

(a) 4.0×14.0 cm² field (X offsets of −24.0 cm, −12.0 cm, 12.0 cm, 24.0 cm and on CAX)
(b) 14×4 cm² field (Y offset of −7 cm, 7 cm and on CAX)
(c) 5.0×5.0 cm² field (X offset of −18 cm, 18 cm and on CAX)
Percentage differences in parentheses are relative to measured data
the offset reduces to $X = \pm 12.0\ cm$ the average differences reduce to $2.8\%$ ($-12.0\ cm$) and $5.3\%$ ($12.0\ cm$). On central axis the average percentage difference is $0.5\%$. Clearly as the offset is reduced for either direction, differences decrease and are larger in the positive $X$ direction.

Measured and Monaco OF discrepancies in the $-X$ direction have a larger absolute average percentage difference ($-4.1\%$ at $-24.0\ cm$ and $-1.9\%$ at $-12.0\ cm$) compared to differences in the $X$ direction ($-1.9\%$ at $24.0\ cm$ and $0.9\%$ at $-12\ cm$). On CAX the average percentage difference is $0.6\%$.

The output factors for the $14.0 \times 4.0\ cm^2$ field shifted in the $\pm Y$ directions are shown in Table 2.b. Average percentage differences between measured and MU2net output factors in the $\pm Y$ directions and on CAX are $1.1\%$ and $-0.6\%$ respectively. Similarly, for measured and Monaco output factors, the average percentage differences are $0.3\%$ in the $\pm Y$ directions and $0.5\%$ on CAX.

Output factors for $5.0 \times 5.0\ cm^2$ square fields $\pm 18.0\ cm$ off axis in the $X$ direction and $\pm 4.0\ cm$ off axis in the $Y$ direction are shown in Table 2c. Following the trend in Table 2a, the average percentage difference between measured and MU2net for the fields at $X = +18.0\ cm$ and $X = -18\ cm$ off axis is $8.9\%$ and $6.6\%$ respectively. On CAX the percentage difference is $-1.2\%$. For measured and Monaco output factors, the average percentage difference for the off-axis field in the $-X$ direction is $-2.2\%$, and $1.2\%$ in the $+X$ direction. On CAX the percentage difference is $0.1\%$.

### Table 3
IMRT plans collapsed to zero beam angles: Percentage differences of Monaco and MU2net point dose DRP comparison for each individual beam

| Site                 | Beam # | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 |
|----------------------|--------|----|----|----|----|----|----|----|----|----|----|----|
| 11 Field             |        | -1.7 | 0.2 | 2.9 | 1.6 | 1.2 | 4.1 | -1.0 | -2.9 | -2.7 | 0.8 | 1.4 |
| Head & Neck          |        | -0.1 | -0.5 | 3.9 | 2.5 | 2.9 | -1.0 | 3.9 | 0.3 | -1.2 |    |    |
| Prostate 9           |        | -0.6 | 0.5 | 4.2 | 0.3 | 0.5 | 0.2 | -0.1 | -0.1 | -0.2 | 1.2 |    |
| Multitarget          |        | 0.5 | 0.7 | 2.2 | -0.4 | 0.5 | 3.2 | -1.0 |    |    |    |    |
| Prostate 1           |        | 1.5 | 2.0 | -0.6 | 2.4 | 0.5 | -1.6 | -1.7 |    |    |    |    |
| Prostate 2           |        | 0.9 | 3.7 | 0.1 | 4.2 | 0.4 | 2.1 | 2.5 |    |    |    |    |
| Prostate 7           |        | -2.7 | 3.0 | 0.9 | 2.4 | -2.5 | -2.8 | 0.7 |    |    |    |    |
| Abdomen              |        | 3.0 | 1.9 | 2.1 | -0.9 | 1.1 | -0.2 |    |    |    |    |    |
| Lung                 |        | 2.0 | 4.3 | 1.2 | 1.6 | 0.0 |    |    |    |    |    |    |

### Table 4
IMRT plans with planned beam angles: Percentage differences for Monaco and MU2net point dose DRPs for individual beams as well as average percentage differences (Avg Diff) for all beams of each plan $\pm 1.0$ standard deviation

| Site       | Planned beam angles | Avg Diff ($\% \pm SD$) |
|------------|---------------------|------------------------|
| 11 Field   | **G 162** **G 130** **G 97** **G 65** **G 32** **G 0** **G 324** **G 292** **G 259** **G 227** **G 195** | 0.4 $\pm$ 2.4 |
| Head & Neck | **G 160** **G 120** **G 80** **G 40** **G 0** **G 320** **G 280** **G 240** **G 200** | 0.4 $\pm$ 3.1 |
| Prostate 9 | **G 160** **G 120** **G 80** **G 40** **G 0** **G 320** **G 280** **G 240** **G 200** | 0.6 $\pm$ 2.8 |
| Multitarget | **G 153** **G 102** **G 51** **G 0** **G 306** **G 255** **G 204** | -0.2 $\pm$ 3.4 |
| Prostate 1 | **G 183** **G 132** **G 81** **G 30** **G 336** **G 285** **G 234** | 2.0 $\pm$ 4.2 |
| Prostate 2 | **G 153** **G 102** **G 51** **G 0** **G 306** **G 255** **G 204** | 1.1 $\pm$ 2.4 |
| Prostate 7 | **G 154** **G 102** **G 50** **G 0** **G 310** **G 258** **G 206** | 0.9 $\pm$ 1.6 |
| Abdomen    | **G 165** **G 105** **G 60** **G 30** **G 0** **G 320** | 1.7 $\pm$ 2.0 |
| Lung       | **G 195** **G 35** **G 0** **G 300** **G 246** | 3.2 $\pm$ 1.3 |
|           | 3.5 | 4.0 | 1.0 | 3.1 | 4.2 |    |    |    |    |    |    |    |
Sample IMRT plans

With individual beams calculated perpendicularly from gantry zero, plan specific percentage point dose differences for MU2net and Monaco are shown Table 3. It is observed that with a DRP selected for each beam, all differences between Monaco and MU2net DRPs are less than ±5.0%.

Point dose comparisons for all IMRT plans with their beams calculated at planned treatment angles are shown in Table 4. With DRPs selected per beam, Monaco and MU2net agree within ±5.0% for all plans.

Clinical cases

A summary of the percentage differences between MU2net and Monaco DRPs bins for each of 1552 treatment beam is displayed in Fig. 10. The beams are split into two categories: prostates (895 beams) and nodes/vesicles (657 beams). MU2net point doses tend to be greater than Monaco for the same DRP. Overall, for the prostate fields (average segment size is 28.87 cm²) and nodal fields (average segment size is 7.09 cm²), the proportion of DRP discrepancies within ±5.0% for the prostate and nodal beams are 84.7% and 73.8%, respectively. In addition, the average segment area for each beam was recorded and correlated with the Monaco versus MU2net percentage differences, to see if any field size dependence was evident. The relation between the DRP % discrepancies bins and their respective segment area for each beam, as well as the number of beams in each range, is summarized in Table 5. Even though the standard deviation is relatively large, it is relatively consistent for each site. For the nodes/vesicles the segment area is smaller compared to the prostate cases and most points still pass within ±5.0%.

Discussion

For the on-axis field sizes ≤ 15.0 × 15.0 cm², the agreement between MU2net and measured data is acceptable. However, it appears that MU2net is not suitable for calculating output factors for larger field sizes. This is a result of the current dose calculation engine and it has little clinical impact on our patient treatments, as segments are smaller than 10 cm.

Table 5 Average segment area for each % difference range for Monaco versus MU2net, ±1 standard deviation as well as the number of beams in each range

| Difference (%) | Prostates | Nodes/Vesicles |
|----------------|-----------|----------------|
|                | Avg Segment Size (cm²) | SD | # of beams | Avg Segment Size (cm²) | SD | # of beams |
| (∞, −5]        | –          | –          | –          | 4.16 | 1.91 | 15 |
| (−5,5]         | 29.24      | 7.05       | 766        | 7.39 | 3.19 | 568 |
| [5,6)          | 29.46      | 6.63       | 58         | 6.39 | 2.62 | 29  |
| [6,7)          | 25.39      | 8.06       | 39         | 6.02 | 2.39 | 20  |
| [7,8)          | 24.87      | 6.53       | 16         | 5.60 | 2.06 | 13  |
| [8,9)          | 22.27      | 6.05       | 8          | 4.02 | 1.99 | 10  |
| [9,10]         | 21.27      | 4.51       | 6          | 3.44 | 0.70 | 4   |
| [10,∞)         | 23.11      | 5.50       | 2          | 3.77 | 0.99 | 10  |
The cryostat characterisation (Fig. 4) exhibits approximately a 3.0% maximum variation in output at the isocentre. In addition to the cryostat, the treatment couch and posterior coil contribute to the overall beam attenuation. Fig. 8 shows that for gantry angles of 0.0°, 30.0°–105.0° and 255.0°–345.0°, measured and Monaco normalised output values for a 5.0×5.0 cm² field are in good agreement. For these angles the beam does not traverse the couch or posterior coil. In the range 120.0° to 240.0° discrepancies between measured and Monaco are observed, with Monaco output consistently lower than measured data. The maximum difference is 3.3% at 120.0° and the minimum is 1.4% at 240.0°. This suggests that the current modelling of the couch and posterior coil in Monaco overestimates the combined attenuation. At present MU2net dose computation incorporates couch attenuation but does not account for cryostat and posterior coil attenuation. Hence for gantry angles 0.0°–105.0° and 255.0°–345.0° differences between MU2net and measured data (Fig. 8) are associated with lack of cryostat modelling. Discrepancies at angles 120.0°–240.0° are potentially associated with deficiencies in the modelling of all sources of beam attenuation.

Comparison of measured and Monaco output factors, shows that the off-axis point doses in the—X direction have a greater discrepancy compared to corresponding fields in the X direction. However, the opposite is the case when comparing measured with MU2net output factors. For off axis fields at 12.0 cm and 24.0 cm in either X direction the discrepancy between MU2net and measured output factors is within the range 3.0 to 12.0%. These larger discrepancies are unclear; however, they could be attributed to the limitation of the Clarkson algorithm for off-axis fields as well as the use of $B_0=0$ T profiles used in MU2net.

All DRP discrepancies for Monaco and MU2net were within ±5.0% for SSIMRT beams delivered at collapsed to zero and planned gantry angles. It should be noted that the variation between fluence and segmentation gives rise to different degree of DRP discrepancies.

Overall, for all 1552 fractions delivered, approximately 80.0% of Monaco versus MU2net DRP discrepancies are within ±5.0%. Therefore, discrepancies for prostate beams are on average less than that for nodes/vesicles and this in part is due to the fluence and the ability to select DRPs in regions of uniform dose. Given the frequency of MU2net-Monaco discrepancies $>\pm 5.0%$ observed in this work, the suitability of MU2net as a standalone independent dose check must be considered within such limitations. To date the follow up QA plan for each film-Monaco planar dose comparison has achieved gamma values pass rates $>95\%$ even though that for some beams the DRP discrepancy is $>\pm 5.0\%$. Taken in conjunction with reference plan gamma analysis, a 5.0% absolute difference between baseline DRP discrepancies and adaptive plan DRP discrepancies for a given beam is considered acceptable. On this basis MU2net provides assurance of adaptive online planning and if the reference plan passes QA, the accuracy of the TPS calculation for these segments on our QA phantom is verified. When MU2net and Monaco have a DRP discrepancy between 5.0–10.0%, this is attributed to the limitation of the MU2net algorithm. Since no evident effect on segment size with DRP discrepancies can be observed. Therefore, the reference plan allows us to identify the beams MU2net has more difficulties with to accurately compute the dose for. For these beams during the adaptive planning, a discrepancy smaller than $\pm 5.0\%$ between Monaco and MU2net will not be expected. It has been observed that discrepancies between MU2net and Monaco throughout treatments remain within $\pm 5.0\%$ of those for the reference plan. In addition, after each fraction the newly created adapted plan undergoes the same QA as the reference plan to independently verify the TPS accuracy.

**Conclusion**

The use of MU2net as a secondary dose check for the Elekta Unity MR-Linac has been investigated. For G0 acceptable discrepancies are observed for central axis square fields < 15×15 cm². However, off-axis fields exhibit greater discrepancies and this requires further investigation outside the scope of this work. Clinically relevant patient specific QA results exhibit differences with the Monaco TPS of $<\pm 10.0\%$, with most differences for the beams of all plans being less than $<\pm 5.0\%$. In the clinical workflow MU2net can be used to interrogate adaptive plans and provide a sanity check for Monaco dose calculations. However, it is recommended to correlate MU2net DRPs with pre and post treatment dosimetry verification. The MU2net dose computation time of approximately 1.0 min for all clinical treatments reported in this work is acceptable. The inclusion of modelling for the posterior coil and cryostat in the MU2net dose computations would be beneficial.

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**Data Availability** All data relevant to this article can be made available upon request.

**Declarations**

**Conflict of interest** The authors have no relevant financial or non-financial interests to disclose.
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