Efficiency and Accuracy Improvements for Patient Plan Quality Assurance with a Passive Scattering Proton Therapy System

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PURPOSE

All proton therapy plans for treatment at our institution using the Mevion S250 passive scattering therapy system are verified for correct monitor units by patient-specific dosimetric measurements. We describe software methods that are designed to streamline the workload, improve accuracy, and reduce the possibility of errors in the overall process of plan quality assurance and monitor unit determination.

OBJECTIVES

The project has two components. The first is to simplify the model that predicts the monitor unit (MU) appropriate for each beam, by using features of the treatment planning system that can be broadly verified by independent measurements. The second objective is to improve the software tools used to compare measured and predicted (by the treatment planning system) dose distributions. The software improvements allow for the analysis of arbitrarily shaped regions-of-interest (ROI), and particularly those that follow isodose contours.

METHODS

Clinical proton therapy plans were created with a pencil-beam double-scattering model for a Mevion S250 system using the RayStation version 6 treatment planning system (RS6-TPS). The Mevion S250 has 24 beam options, organized into three categories (Small, Deep, and Large) according to the type of upstream scatterers used. Patient plans consist of a set of beams specified by option, range, modulation, and patient-specific aperture and compensator, along with geometric parameters. The patient plan is transferred by the TPS to a homogeneous cubical phantom, and this "QA plan" is then used for measurements to determine the correct delivery MU value.

QA plans are constructed one for each beam by transferring the beam aperture, compensator, and RS6-TPS internal proton fluence to a homogeneous phantom. A Python script within the RS6-TPS generates a spreadsheet with parameters to be used for the QA measurements. The measurements are made using a MatrixX™ (IBA Dosimetry) planar ionization detector array, with a build-up chosen to place the detector plane near the mid-point of the beam spread-out Bragg peak (SOBP). Analysis of the agreement between RS6-TPS and measurement is done initially using the myQA ™ software (IBA Dosimetry) and subsequently with an in-house software tool for arbitrarily shaped ROI's.

Measurements are made initially using the predicted MU from the Meterset-to-MU conversion factors determined in our model.
Measurements that indicate an MU adjustment of more than a set tolerance will be required are repeated after making the MU adjustment.
It is clear that the QA plan does not have the same tissue scattering as the phantom, which is often called the patient-scatter factor (PSF) [1, 2]. In our procedure, we rely on the TPS to transfer the same proton fluence used in the patient plan to the QA plan, a process which is identical to how most photon IMRT QA is done. CONTINUED ON RIGHT-HAND PANEL

RESULTS

From a set of over 500 measurements, fits of Meterset (RS6-TPS predicted "MU") to measured plan MU were generated, extracting the best straight-line fit for each individual option. As expected, the fit parameters were extremely well correlated to a linear fit, and the slope of the fit varied from option to option. R-squared values for all options were above 0.9899. Linear fits using a slope and offset value were tested both with a best-fit offset and with the offset forced to be zero (since zero delivered MU should match zero dose). Due to statistical fluctuations In the measured data a slightly better fit is found when the offset value is allowed to vary from zero by a small amount.
Measured MU fits to RS6-TPS Meterset values were determined over the entire range of clinically utilized MU values, representing dose-per-fraction ranging from approximately 50 CcGE to hypofractionation values over 5 CcGE (see Figure 1).

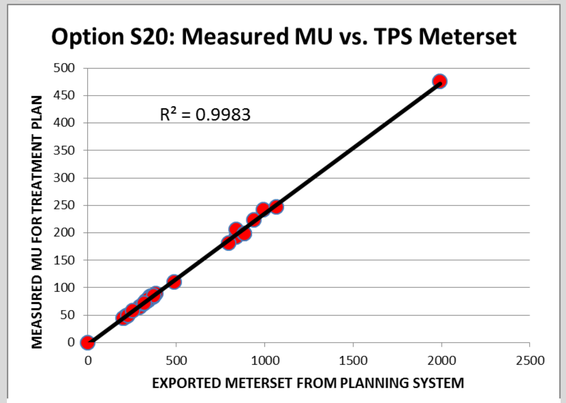

FIGURE 1: DETERMINING METERSET FACTORS

The comparison of measured beam profiles to RS6-TPS predictions are initially completed using the IBA-Dosimetry myQA™ software. A limitation of this approach is that the software only permits single-point or rectangular regions-of-interest (ROI) to be used in determining the fit of measurement to data. This makes it impossible to select the region of the dose distribution following the contour of the penumbra, if the aperture shape is not approximately rectangular. The majority of treatment cases do not have a rectangular shape.

To overcome this limitation, an independent software tool was written (called internally "myQAroi"), which analyzes an arbitrarily shaped polygonal ROI (see Figure 4). The tool allows the ROI to be defined using an isodose line if desired. The tool also determines the relative MU scaling that would produce the highest pass rate in comparing measured to calculated dose. As a complement to the myQA™ analysis, which uses a "gamma function" comparison, the myQAroi tool optimizes based on point-by-point agreement of the absolute value of dose difference. This is arguably a stricter constraint, since it does not permit "distance-to-agreement" matching of dose values.

The myQAroi tool was written in Python 3.6 using the open-source version of PyQt5 for the user interface components, and numpy and scipy for numerical functions. An interface to read IBA-Dosimetry opg files is used to convert the measured dose distributions into numpy arrays.

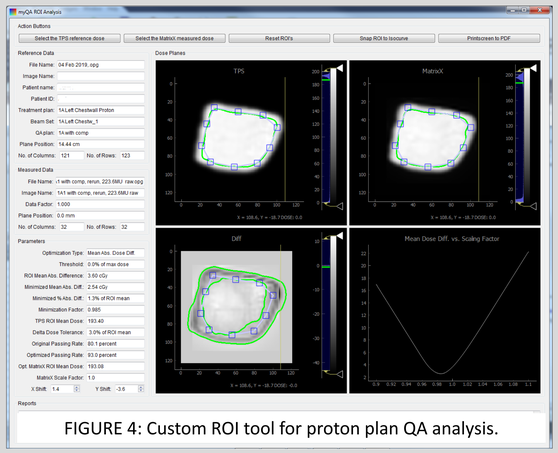

FIGURE 4: Custom ROI tool for proton plan QA analysis.

The linear fits are then used to calibrate the internal RS-TPS value of Meterset to the expected MU value for the plan. The expected value is used to begin the QA process, by delivering that value of MU and measuring the resulting dose distribution with the MatrixX. For the deep options used in approximately 40% of the on-treatment plans, the agreement between measured and expected calibrated MU is typically within 1%.
If the difference between the predicted "expected" MU value and the measured MU value exceeds a threshold (set variously from 2% to 5%), the QA measurement is repeated with the corrected MU value, so that the final agreement is within 2%. This is a very conservative procedure, since MU scaling based on measurement relies only on the MU-dose linearity of the S250, which is independently verified by machine QA.
This procedure relies on the ability of the RS6-TPS to correctly compute the Range and Modulation dependence of the MU-to-Dose calibration. We have verified this explicitly by comparing measured values of the modulation dependence of the options-specific output factors to the values predicted by the RS6-TPS. This is done by taking the calculated dose distribution for the SOBP in a phantom, and using the entrance dose, corrected by inverse-square, as a surrogate for the dose measured by the monitor unit chamber in the S250. Agreement between actual measurement and this "virtual" output factor measurement is excellent. We note that the modulation dependence of output factor is also predicted well by the Bortfeld model [3, 4] with parameters adjusted to the beam option (see Figure 2).

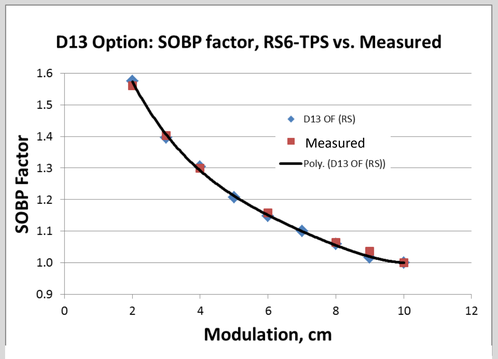

FIGURE 2: Modulation dependence of SOBP factor.

Patient specific proton QA measurements are made on a nightly basis, analyzed the next day, and any results that exceed tolerance are scheduled for a repeat measurement. In order to reduce hand-entry of data for the QA measurements, a script was written for RS6-TPS that prepares a spreadsheet with the conditions for the measurement, and also records detailed information on the beam parameters. This allows for retrospective data-mining of beam data and refinement of the models used for MU prediction
(See Figure 3).

PLAN INFORMATION		WITH COMPENSATOR		ANALYSIS	
Patient Information		**Measurement 1**		**MU Check**	
Patient Name	Anonymous, Patient	**Compensator?**	IN	Scaled RS Meterset	
Patient MR #	A123456	**Location (enter any shifts)**	ISO	TPS Meterset:	**984.7**
Plan Name	3A Liver HCPT	**WED (cm)**	6.59	Conversion Factor:	**0.2356**
		P-A (QA plan)	8.41	TPS Calculated MU:	**232.0**
Patient Plan		**MatrixX Buildup (cm)**	5.8	DAILY OF CORRECTION [%]	**0.0%**
Field ID	3A1	QA Dose Expected, cCGE	254.9	TPS Calculated MU, corrected:	**232.0**
BeamSet Name	3A Liver	QA MU Delivered	233.4	Measured Plan MU:	**233.4**
MEVION Option ID	L6	QA Dose measured (cCGE)	253.8	%(TPS-Meas.)/TPS:	**-0.58%**
Range (cm)	14.8	myQA scaling factor (actual)	1.0043		
Modulation Width (cm)	10.8	Gamma pass (%)	**99.9%**		
Field Radius, cm (Mosaiq)	7.507	**Result**		**MU Calculation Summary**	
Gantry Angle (deg)	150.0	QA MU to match QA plan	234.4	Patient:	**Anonymous, Patient**
Couch Angle (deg)	180.0			MR#:	**A123456**
Snout ID	Large Applicator	**Measurement 2 (if required)**		Field Name:	**3A1**
Air Gap (cm)	11.7	**Compensator?**	IN	Range Option:	**L6**
Snout Position (cm)	31.5	**Location (enter any shifts)**	ISO	TPS/Measured diff [%]:	-0.58%
Field size Equiv. R	6.1	**WED (cm)**	6.59	Daily OF Correction, %:	0.0%
SAD X	173.4	**P-A (QA plan)**	8.41	Gamma pass, NO COMP:	99.9%
SAD Y	173.4	**MatrixX Buildup (cm)**	5.8	Gamma pass, WITH COMP:	99.9%
Plan Beam Dose (cCGE)	258.4	QA Dose Expected, cCGE	254.9	MU DETERMINED FROM:	COMPENSATOR
Beam Depth (cm, physical)	11.4	QA MU Delivered		MU for plan	233.4
		QA Dose measured (cCGE)		Measured OF (cGy/MU)	**1.0084**
		myQA scaling factor (actual)			
		Gamma pass (%)			
		Result			
		QA MU to match QA plan			

FIGURE 3: Spreadsheet (partial) auto-generated by RayStation script.

METHODS, cont.

The RS6-TPS does not currently have a facility for calibrating the internal proton fluence in terms that can generate an actual MU value for treatment. However, the RS6-TPS algorithm does include a factor which is linearly proportional to the proton fluence. This feature is essential for the effective transfer of patient plan fluence to QA plan phantom. The factor is exposed in the treatment plan as "MU", although it is not calibrated. In addition, this factor does not transfer from one option to another; in other words, the proportionality of the MU-factor to actual proton fluence is not constant from one beam option to another. For clarity in distinguishing actual machine MU from the TPS internal representation, we call the TPS values "Meterset Values" (after the DICOM field designation).

It is trivial to demonstrate that the Meterset value is linearly proportional to dose within the RS6-TPS itself. To use this value in patient plan QA, we needed to verify that it was linearly proportional to measured MU for actual plans, for each option, over a wide range of delivery MU.
Over an extended period, we performed patient plan QA both with and without patient plan compensators in place, recording the RS6-TPS Meterset value and the final determined MU, along with any daily variations in machine output. In principle, the values of measured MU should be identical with and without the compensator, but in practice there were small variances, particularly for the Large options. Measurements without the compensator have the advantage that the isodose planes are parallel to the phantom surface (and detector plane), which helps avoid measuring in a region of dose gradient. On the other hand, measurements with the compensator are expected to better mimic the actual patient treatment plan.

CONCLUSION

We have verified that the internal MU values reported in the RayStation-6 double-scattering proton plans (Meterset) can be used as initial predictors of treatment MU in advance of QA measurements, by determining the option-specific linear relationship between Meterset and MU.

A software tool that allows for matching measured and predicted dose distributions within an arbitrarily defined ROI shape has the potential to improve the accuracy of dose distribution in passive-scattering proton treatments.

REFERENCES

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