Sensitivity evaluation of two commercial quality assurance systems to organ-dose variations of patient-specific VMAT plans

Oluwaseyi M. Oderinde and Freek Du Plessis
Department of Medical Physics, University of the Free State, Bloemfontein Republic of South Africa

ABSTRACT
The purpose of this study was to assess the dose variation sensitivity of two quality assurance (QA) devices (Integral quality monitoring (IQM®) and MatriXXEvolution systems) used for radiotherapy verification. Six volumetric-modulated arc therapy (VMAT) radiation plans were calculated, namely, three head-and-neck and three prostate cases. For sensitivity evaluation, the planning target volume (PTV) dose for each patient’s plan was modified by 0.5%, 1.0%, 2.0%, and 3.0% of its original dose. The IQM and MatriXX detectors are sensitive to the dose errors considered. At 0.5% PTV dose modification, the average local percentage differences for the IQM are 0.27 ± 0.29, 0.24 ± 0.33, 0.42 ± 0.39, 0.74 ± 0.28, 0.41 ± 0.24, and 0.26 ± 0.32, while the average local percentage differences for the MatriXX device are 1.37 ± 0.25, 1.30 ± 0.75, 2.82 ± 1.46, 1.34 ± 1.29, 1.58 ± 0.97, and 1.13 ± 0.97. The sensitivity of the detectors is more pronounced in VMAT plan errors containing larger segments. This shows that the sensitivities of the detectors are plan and fraction specific. Both detectors are sensitive to dose variation in the clinical plans to a minimal dose deviation of 0.5%. The IQM detector shows the capability to be used for QA procedures and for real-time beam output monitoring.

1. Introduction
The clinical effectiveness of advanced radiotherapy (RT) such as intensity-modulated radiotherapy (IMRT) and volumetric-modulated arc therapy (VMAT) techniques depends on efficient treatment planning (TP) and quality assessment strategies (Rangel, Palte, & Dunscombe, 2010; Yan et al., 2009). VMAT has contributed immensely to the clinical and physical aspects of radiation treatment. However, this treatment modality is accompanied by difficulties in performing its quality assessment procedures for patient-specific quality assurance (QA), treatment delivery units, and treatment planning system (TPS). Also, time constraints complicate patient dose QA on a daily basis due to the workload at RT centers which scales with an increase in cancer treatment cases. To raise the confidence level of advanced RT treatment modalities, fast and efficient pretreatment/online dose verification is necessary. An intensive patient-specific dose verifying system should be capable of detecting minimal dose variations/modifications in patients’ treatment plans.

The use of film and ionization chamber has widely been employed for VMAT QA procedure, but it was reported that the use of film is affected by external conditions such as external light and processing time (Son et al., 2015). This has led to the design of fast automated readout with high-efficiency systems such as 2D plastic scintillation detector arrays, e.g. OCTAVIUS, ArcCHECK/MapCHECK, MatriXX with COMPASS, electronic portal imaging device, DAVID™ System, Dolphin®, Magic Plate, VANILLA, Delta4 Discover, and the double wedge-shaped ionization chamber IQM system (Casar et al., 2017; Fuangrod et al., 2016; Hoffman, Chung, Hess, Stern, & Benedict, 2017; Islam et al., 2009; Li et al., 2013; Louwe et al., 2015; Myers, Stathakis, Buckey, & Papanikolaou, 2013; Oinam, Singh, Sharma, & Goswami, 2009; Poppe et al., 2006; Björn, 2010; Sanatorium, Valley, & Kong, 2012; ScandiDos, 2016; Shimohigashi et al., 2012; Stelljes et al., 2015; Theolking et al., 2016; Velthuis et al., 2014; Wendling et al., 2006; Wong et al., 2012; Woodruff et al., 2015). These QA systems have generally been accepted for VMAT quality assessment procedures.

In previous studies, the IQM and MatriXX detectors were evaluated based on their error sensitivity (outlined in Table 1). Articles have shown the sensitivity of the IQM and MatriXX to multi-leaf collimator (MLC) positional shift, but little has been achieved about dose variation sensitivity of the detectors. Hoffman et al. (2017) investigated the sensitivity of a regular field of 10 × 10 and 1 × 1 cm² square field and nine static MLC IMRT treatments for head-and-neck cancer regions whereby the study modified a single MLC position at 1 mm. They concluded that the IQM detector is sensitive to single MLC leaf positional error of IMRT plans and 1 × 1 cm² square field, but it is less sensitive...
to the single positional error of $10 \times 10$ cm$^2$ square field. The study also evaluated 1% dose error for a regular small field at 100 monitor unit which was concluded to be sensitive. Islam et al. (2009) evaluated the sensitivity of the IQM system for an MLC leaf bank error of 1 mm on a $15 \times 15$ cm$^2$ square field. It was concluded that the device is capable of detecting leaf bank errors at this field size. Shang, Godley, Huang, Qi, and Xia (2017) assessed the sensitivity of the MatriXX detector to $\pm 1$ and 2 mm alterations of MLC leaves of two IMRT plans of prostate and head-and-neck cancers. Their study reported that the MatriXX is sensitive to leaf positioning shifts of $\pm 2$ mm with a pass rate of 95% at gamma criterion of 3%/3 mm. All the above sensitivity studies of the IQM and MatriXX detectors focused majorly on MLC positional errors, and their sensitivities were quantified as a local percentage difference and decrease in gamma pass rate for IQM and MatriXX detectors, respectively.

Another study has evaluated the sensitivity of the IQM device to several alterations of 11 segments using the EGSnrc/BEAMnrc Monte Carlo simulation. The MLC positions were shifted randomly within $\pm 1$, 2, and 3 mm (Oderinde & Du Plessis, 2017). This study aimed to evaluate the sensitivity of the IQM and MatriXX QA systems to dose error of patient-oriented plans. The sensitivity assessment of this study was used to determine a reasonable tolerance for each detector.

2. Materials and methods

2.1. Quality assurance systems

RT QA systems are conventionally used for verifying and validating patients’ treatment plans for offline and online treatment. The QA systems considered in this study are the IQM and the MatriXX detectors. The physical properties of the detectors are summarized in this section.

Integral quality monitoring (IQM) system is a double wedge-shaped ionization chamber that is capable of verifying the accuracy of patient TP data on a segment-by-segment basis in real time. The IQM can also function as a pretreatment and machine QA tool (Islam et al., 2009). It is fixed to the linac head with the gradient of the ionization chamber directed along the MLC leaf motion. Islam et al. (2009) initiated the integral quality monitoring (IQM) system which comprises an area integrating energy fluence monitoring sensor (AIMS) and calculating module IQM_CAL (Islam et al., 2009). The IQM® system was released by IRT Systems GmbH, Koblenz, Germany. The commercial IQM detector has a large sensitive area ($26 \times 26$ cm$^2$) ion chamber that can accommodate a $40 \times 40$ cm$^2$ open field defined at 100 cm source to surface distance.

MatriXX$^\text{evolution}$ System is a device that consists of 1020 air-vented ionization chambers located on a $32 \times 32$ grid. Each of the 2D array ionization chambers has a sensitive volume, diameter, height, and detector spacing of 0.08 cm$^3$, 4.50 mm, 5.00 mm, and 7.62 mm, respectively. It operates at a potential of 500 V, and it has a sensitive area of $24 \times 24$ cm$^2$. MatriXX$^\text{evolution}$ functions as pretreatment QA system whereby it verifies the patient’s treatment plan offline. It is attached to the gantry head with the aid of the gantry head holder.

Both systems allow for beam output measurement at any gantry angle, allowing for detection of gantry-related beam output deviation.

2.2. Treatment plan selection and delivery

Six treatment plans (three VMAT head-and-neck and three VMAT prostate plans) were selected for this study as indicated in Table 2. The treatment plans (shown in Figure 1) were modeled and optimized with the Monaco TPS (v.3.4, Elekta AB, Sweden). Its dose calculation is based on the Monte Carlo algorithm XVMC. The treatment plans were transferred to the linac for dose delivery using the MOSAIQ radiation oncology information system. An Elekta Synergy linac equipped with an Agility 160 MLC and a nominal acceleration potential of 10 MV was utilized in delivering the calculated dose to be measured by the IQM and MatriXX QA systems.

| S/N | TP regions and types       | No. of segments | PTV doses (cGy) |
|-----|---------------------------|----------------|-----------------|
| 1   | VMAT head-and-neck        | 103            | 212             |
| 2   | VMAT head-and-neck        | 131            | 200             |
| 3   | VMAT head-and-neck        | 94             | 212             |
| 4   | VMAT prostate             | 96             | 309             |
| 5   | VMAT prostate             | 96             | 306             |
| 6   | VMAT prostate             | 97             | 306             |
Figure 1. Original patient plans used in this study (1, 2, and 3: prostate plans and 4, 5, and 6: head-and-neck plans).

Figure 2. In panels a, c, and e, the IQM cumulative response to head-and-neck patient plans for dose variations of 0.5%, 1.0%, 2.0%, and 3.0% of the original PTV dose is shown. Due to the closely spaced curves, the local percentage differences of the dose error plans with respect to the baseline dose are shown in panels b, d, and f.
2.3. Organ dose variation and measurement

Within MOSAIQ, the planning target volume (PTV) dose of the treatment plans was altered per fraction at 0.5%, 1%, 2%, and 3% of their original planned PTV dose while keeping the other TP parameters unchanged. Afterward, the original and modified treatment plans were transferred to the linac for delivery. The plans were measured using the IQM and MatriXX systems. For each plan measured, the IQM signals were recorded on excel sheet in the IQM database for further analysis, while the MatriXX recorded all subfields of all the control points for each VMAT plan as one integral dose on the OminiPro-l’mRT v.1.7 software. After that, error plan signals were compared with the baseline signals for the IQM and MatriXX sensitivity evaluation.

3. Results

Figures 2 and 3 show the IQM signal response to VMAT plans considered in this study. The original target dose for each VMAT plan was altered by 0.5%, 1.0%, 2.0%, and 3.0%. Local percentage differences

Table 3. Average local percentage difference for the modified dose of patient plans considered in this study.

| Detectors | Error (%) | IQM | MatriXX |
|-----------|-----------|-----|---------|
|           | +0.5      | +1.0| +2.0    | +3.0    |
| HnN Plan 1| 0.27 ± 0.29| 1.13 ± 0.309| 2.06 ± 0.35| 3.26 ± 0.40| 1.37 ± 0.25| 2.51 ± 0.67| 3.75 ± 1.12| 4.89 ± 1.66|
| HnN Plan 2| 0.24 ± 0.35| 1.09 ± 0.59| 1.80 ± 0.74| 2.71 ± 0.59| 1.30 ± 0.75| 2.75 ± 1.39| 3.91 ± 1.97| 5.39 ± 2.82|
| HnN Plan 3| 0.42 ± 0.39| 1.44 ± 0.61| 1.99 ± 0.57| 3.24 ± 0.83| 2.82 ± 1.46| 4.19 ± 2.36| 5.29 ± 3.09| 7.15 ± 4.29|
| Prs Plan 1| 0.74 ± 0.28| 1.35 ± 0.28| 2.27 ± 0.25| 3.13 ± 0.26| 1.34 ± 1.29| 2.76 ± 2.22| 3.77 ± 3.16| 5.39 ± 3.52|
| Prs Plan 2| 0.41 ± 0.24| 1.15 ± 0.26| 1.92 ± 0.29| 2.34 ± 0.29| 1.58 ± 0.97| 3.10 ± 1.23| 4.26 ± 1.32| 5.05 ± 1.59|
| Prs Plan 3| 0.26 ± 0.32| 1.07 ± 0.59| 1.72 ± 0.58| 2.26 ± 0.53| 1.13 ± 0.97| 2.05 ± 1.43| 3.04 ± 2.04| 4.21 ± 3.07|
Figure 4. MatriXX signal response to head-and-neck patient plans for dose variation of 0.5%, 1.0%, 2.0%, and 3.0% of the original PTV dose. Panel a shows H&N (plan 1, 103 segments), while panel b shows the local percentage difference of this plan. Panel c shows H&N (plan 2, 131 segments), and panel d shows its local percentage difference. Panel e shows H&N (plan 3, 97 segments) and panel f shows the local percentage difference of plan 3.

Figure 5. MatriXX signal response to prostate patient plans for dose variation of 0.5%, 1.0%, 2.0%, and 3.0% of the original PTV dose. Panel a shows prostate (plan 1, 96 segments), while panel b shows the local percentage difference of this plan. Panel c shows the prostate (plan 2, 96 segments) and panel d shows its local percentage difference. Panel e shows prostate (plan 3, 97 segments) and panel f shows the local percentage difference of plan 3.
show that the IQM device is sensitive to dose distortion as low as 0.5% of the original PTV plan dose. Table 3 summarizes the average local percentage differences for the head-and-neck and prostate plans considered in this study. The table shows that an increase in distortion percentage causes an increase in signal response of the IQM device to VMAT plans considered in this study. To 0.5% dose modification, IQM has an average percentage difference of 0.27 ± 0.29, 0.24 ± 0.35, 0.42 ± 0.39, 0.74 ± 0.28, 0.41 ± 0.24, and 0.26 ± 0.32 for the six VMAT plans. Figures 4 and 5 show the MatriXX signal response to dose errors. The chart graphs show signal deviations due to systematic errors that modified the PTV dose. An increase in dose error of VMAT plans causes an increase in signal deviation of the MatriXX device. The average local percentage difference (in Table 3) increases with an increase in the invoked percentage dose error of the VMAT plans. For example, 0.5% dose deviation has 1.37 ± 0.25, 1.30 ± 0.75, 2.82 ± 1.46, 1.34 ± 1.29, 1.58 ± 0.97, and 1.13 ± 0.97 average local percentage differences for the six VMAT plans. With dose errors of 0.5%, 2.0%, and 3.0%, few of the average percentage difference for IQM device fall below the threshold. This does not necessarily mean that the IQM device is less sensitive compared to MatriXX signal responses. The IQM signals are of the power of five (10^5) which makes the magnitude of the average local percentage differences relatively small. However, the sensitivity of the IQM has revealed the sensitivity of the device to set levels of tolerance. The IQM and MatriXX detectors are sensitive to PTV dose errors as low as 0.5%. This study shows that the IQM and MatriXX^Evolution^ signals are not the same for all the treatment plans considered, and it is obvious that the effect of dose error is dependent on the plans.

4. Discussion

In this study, the sensitivity of the IQM and MatriXX^Evolution^ detectors was assessed by varying organ dose of VMAT plans by 0.5%, 1.0%, 2.0%, and 3.0% of their original plan dose. In VMAT treatment strategy, the accuracy of the dose prescription is essential to avoid treatment complications. This study intentionally modified the prescription dose of the patient-specific plans in order to determine the sensitivity of the two commercial QA systems. The focus of this study is not to directly compare the two detector systems since the detectors do not function in similar ways. The IQM device is designed for real-time beam monitoring during treatment, while the MatriXX detector is used for pretreatment QA fluence measurement with the added component of using the measured machine fluence to reconstruct the dose in the patient model for comparison with the original planned dose.

Our study shows that these commercial detectors are sensitive to PTV dose variations that is detectable at a 0.5% dose alteration level. Figures 2 and 3 show the signal effect of the IQM device to dose error, and Table 3 summarizes the average local percentage difference. Figures 4 and 5 show the MatriXX signal response to dose errors of VMAT plans. Alterations of the PTV dose will not affect the penumbra dose as seen in the MatriXX response charts. Dose errors of 0.5%, 1.0%, 2.0%, and 3.0% of the VMAT plans give a sizeable signal which increases with an increase in dose error percentage. The sensitivity of the QA systems considered in this study varies within the magnitude of the dose error and VMAT plans. The six VMAT plans studied were of complicated treatment sites with over 95 small fractions. Each fraction gives a different and unique signal response to the QA systems. This shows that the signal response of the detectors is segment-to-segment sensitive.

Previous studies have evaluated the dose error sensitivity of Delta^4^, ArcCHECK, OCTAVIUS, and PTW 2D array QA systems using the Rapid Arc and VMAT treatment types whereby the authors used a minimum dose error of 3% (Arumugam, Xing, Young, & Holloway, 2015; Fredh, Scherman, & Fog, 2013). From our study, the IQM and the MatriXX^Evolution^ detectors can be used for QA procedure if a smaller than 3% dose error is required. However, log file analysis has been suggested as another alternative QA procedure which has been tested for MLC error verification, but nothing has been achieved on dose error verification (Kosaka et al., 2016; Kumar, Amols, Lovelock, Sharma, & Datta, 2017; Rahman, Lei, & Kalantzis, 2018).

Scientifically, it is assumed that the wedge-shaped ionization chamber of the IQM device will affect the sensitivity of the chamber along its gradient whereby the sensitivity of the device should increase along its gradient to the large chamber side of the MLC motion. In this study, the sensitivity of the IQM device to dose error shows no statistically significant effect of the side at which the beam aperture was incident on the device. Since the IQM device is also used during the real-time treatment verification, the skin dose and penumbra effects could be accounted for during planning.

According to Wolfsberger, Waqar, Nitsch, Bhagwat, and Zygmanski (2010), the angular effect of the MatriXX detector on the planned dose is up to 11% when the device is positioned on the treatment couch. However, Shang et al. reported that the gantry effect of the 2D array chamber is insignificant of MLC shift. In our study, there is no exhibited sensitivity as a result of the angular effect of the MatriXX on its sensitivity and signal response of the VMAT plans measured. The MatriXX was attached to the gantry headed for all measurements.
It is essential to choose a convenient and best type of metric to evaluate the sensitivity of a QA system. Conventionally in clinical practice, gamma analysis has generally been utilized to assess the sensitivity of a QA device (Hussein, Rowshanfarzad, Ebert, Nisbet, & Clark, 2013; Hwang, Ye, Park, & Kim, 2014; Low, 2010). This generic metric type is not appropriate to analyze the IQM signal. At this stage, the IQM device is designed to generate an integral value of the recorded measurements which could not be examined by either the distance to an agreement or dose difference parameters since the IQM signal is not a function of dose distribution. The IQM signal is a function of the electrical charge which is of the order of nC (nano coulomb). It is an ongoing study on how to relate the IQM output signal to dose. Therefore, local difference percentage is the most appropriate metric type for IQM detector’s signal which was also used for MatriXX signal response for uniformity.

Several errors can contribute to dose distribution in a patient’s treatment plan. To mention a few, such as MLC, planning, software, human, and mechanical errors. This study focused on the composite error which is the dose error that is influenced by the above-listed errors. No matter the source of error that affects the overall dose distribution, the IQM, and MatriXX detectors are capable of detecting such an error to the minimum of 0.5% dose deviation.

5. Conclusion

This study concludes that the IQM and MatriXX detectors are both capable of detecting small systematic dose errors introduced as low as 0.5%.

Disclosure statement

No potential conflict of interest was reported by the authors.

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