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Research/Technical Note

End-to-End Test for a Radiotherapy Program Based on the Medical Linear Accelerator Installed in a Resource-Limited Oncology Centre in Sub-Saharan Africa

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Abstract: Several challenges including the availability of necessary funds and expertise hinder the development and modernization of radiotherapy in resource-scarce countries like those in Sub-Saharan Africa (SSA). This work presents the findings of an end-to-end audit on independent verification of radiation doses delivered by a commercially available medical linear accelerator (linac) installed at Cameroon Oncology Center, a resource-constrained oncology centre in SSA. The medical linac with 6 MV and 18 MV x-rays, and five electron energies ranging from 6–20 MeV was commissioned for clinical use. The mailed TLD dosimetry irradiation systems based on the American Radiological Physics Center technique were used to check the output of the photon beams and electron energies. The end-to-end test was achieved by requesting, imaging and treating the MD Anderson anthropomorphic head and neck phantom using an IMRT technique on our linac. The phantom was irradiated and sent back to the USA for analysis. Evaluation criteria require that an institution's treatment plan agree within ± 7% of measured TLD doses and that ≥ 85% of pixels pass ± 7%/4 mm gamma analysis for film. Beam output met the required criteria within ± 3%, and our institution's treatment plan satisfied the established criteria of measured TLD doses and film dose distributions. The gamma-passing rate was ≥ 91%. A resource-constrained oncology centre in SSA has met the MD Anderson humanoid phantom irradiation criteria generally used for credentialing institutions to assure quality and safety of complex radiation treatments. Despite the various challenges faced by resource-constrained countries in SSA, this work demonstrates the practicability of implementing a modern radiotherapy program based on linear accelerator technology in a resource-limited region.

Keywords: Radiotherapy, Medical Linac, End-to-End Audit, Cameroon Oncology Center

1. Introduction

The estimated number of new cancer cases in Sub-Saharan Africa (SSA) in 2020 was about 800,000 according to the International Agency for Research on Cancer [1–3]. This means that Sub-Saharan African countries must develop policies that would lead to commissioning of many more cancer diagnosing and treatment centers in their countries. Radiation technology plays an essential role in the management of cancer. Radiotherapy (RT) describes the medical application of ionizing radiation for the treatment of cancer. Modern external beam radiation therapy (EBRT) mostly applies to megavoltage electron (6–22 MeV) or x-ray (4–25 MV) radiations produced by medical linear accelerators (linacs). Most advanced conformal EBRT techniques including three-dimensional conformal RT (3D CRT), intensity-modulated radiation therapy (IMRT) and volumetric-modulated arc therapy (VMAT) are delivered on a computer-controlled linac using megavoltage photon beams [4].

It is a well-established fact that most cancers diagnosed in

resource-limited countries like those in SSA are diagnosed at later stages and hence the requirements for RT are even greater. One of the difficulties that has hampered the development of RT facilities in SSA is that RT is capital intensive and requires skilled and certified professionals that takes years to train. Even basic RT based on Co-60 teletherapy equipment was not readily available in SSA as radiation facilities were not available in more than 30 countries in SSA. However, in the recent past, a number of countries in SSA including Ghana, Nigeria, Cameroon, Ivory Coast, Kenya, Rwanda and Uganda have started implementing RT programs based on linac technology. Given this, it is imperative that regulatory bodies and the International Atomic Energy Agency (IAEA) put a quality assurance (QA) program that can be adopted by these countries as well as a system for independent verification of dose and dose distributions. With the increasing deployment of highly sophisticated digital linacs in radiation medicine, many countries in SSA do not have the expertise to perform the necessary QA or may not be aware that QA equipment can add an additional cost of up to 200.000 USD for purchase and use. This is necessary if these sophisticated linacs are to be utilized to their fullest.

According to the IAEA, QA is defined as all procedures that ensure consistency of the medical prescription, and safe fulfillment of that prescription, as regards the dose to the target volume, together with minimal dose to normal tissue, minimal exposure of personnel and adequate patient monitoring. Therefore, QA for a RT program is necessary to ensure that during treatment delivery the patient receives the correct dose since a small inaccuracy in dose could result in a significant deviation from the planned response and could compromise treatment outcome. For tumours, a slight underdose could yield a decrease in the probability of tumour control while, for healthy tissues, a small overdose could yield a considerably higher probability of morbidity [5, 6]. Therefore, following the commissioning of radiation equipment for clinical use, radiation physicists periodically perform various QA tests to verify that all equipment is functioning properly, and that the specifics of dose prescription and treatment plan are correctly delivered to the patient with the basic principle that the radiation dose delivered to the patient should not deviate by ±5% of the prescribed dose [5, 6, 7–12]. Even so, about 150 radiological accidents, involving more than 3000 patients with adverse effects have been reported in the literature [13–18]. Most of the mistakes were related to insufficient implementation of QA. Some of these accidents happened in full-resource countries like France and the United Kingdom. For example, at Beatson Oncology Centre in Glasgow, Scotland [13, 14], and Centre Hospitalier Jean Monnet in Epinal, France [15, 16], there were significant deviation of radiation doses than intended doses by more than 30% in some cases.

The role of dosimetry audits as high-level QA tests to improve both quality and safety in RT is well-known [19–24]. However, many RT centres usually test only specific steps in the RT chain on a regular basis and not the overall process in the planning and delivery of radiation treatments. An end-to-end QA test is a dosimetric audit methodology that tests the entire accuracy of the RT process. By testing whether all the links in the RT chain are functioning correctly, end-to-end QA improves RT practice and ensures its safe implementation. Dosimetry audits vary from postal to on-site visits, and from basic measurements in reference conditions (Level I audit) through a full end-to-end audit (Level III audit) where an anthropomorphic phantom replaces a patient and follows the pathway from imaging through treatment panning to dose delivery [20, 21, 23]. Since complex RT techniques such as IMRT use more fields and monitor units, and cause higher whole-body exposure to leakage radiation compared to 3D CRT [25–27] they require independent audits for accuracy and safety purposes [19].

With the installation and commissioning of Cameroon's first medical linac at our institution, Cameroon Oncology Center (COC), Cameroon now joins a handful of countries in SSA to have this radiation technology. Following the adoption of our own QA program based on international guidelines including the American Association of Physicists in Medicine TG-51 protocol [28] and TG-142 report [8], we undertook to perform an independent dosimetry audit to ensure that our radiation treatment planning equipment has been correctly and adequately commissioned for clinical implementation. The aim of this work is to report the findings of the quality audit on independent verification of radiation doses delivered by the medical linac installed at COC. COC was audited by the American Radiological Physics Center of the MD Anderson Cancer Center in the USA.

2. Methods and Materials

A commercially available Varian Clinac 21EX linac (Varian Medical Systems, Palo Alto, CA) with two photon beams (6 MV and 18 MV) and five electron energies (6 MeV, 9 MeV, 12 MeV, 16 MeV and 20 MeV) was commissioned for clinical use. The linac is equipped with a dynamic wedge and 120 Millennium MLCs (comprising two opposing leaf banks with leaves that move along the X-axis), and a Portal Imager AS500 for correct patient setup. The QA procedures for independent dose verification consisted of verification of the reference output of the beams used for patient treatment, and an end-to-end quality audit for IMRT using an anthropomorphic phantom. TLDs (lithium fluoride dosimeters) and Gafchromic film were employed as radiation dosimeters. Before performing the QA tests, the linac was calibrated as described below.

2.1. Machine Calibration

The 21EX linac was calibrated in accordance with TG-51 protocol [28]. An IBA 1D water phantom, PTW N30001 0.6 cc Farmer chamber (SN: 1230), and Keithley electrometer (SN: 456607) as well as pressure and temperature measuring systems were used for absolute calibrations of the photon and electron energies. Employing the protocol, the absorbed-dose to water D_w^Q at the point of measurement of a calibrated ion chamber placed under reference conditions is

given by:

$$D_w^Q = \mathrm{M} k_Q N_{D,w}^{60Co} \quad (1)$$

Where Q is the beam quality of the clinical photon or electron beam; M is the fully corrected ion chamber reading; $N_{D,w}^{60Co}$ is the absorbed-dose to water calibration factor of an ion chamber; and k_Q is the quality conversion factor, which converts the calibration factor for a ^{60}Co beam to that of a beam of quality Q. For an electron beam,

$$k_Q = P_{\mathrm{gr}}^Q k_{R_{50}} \quad (2)$$

Where $k_{R_{50}}$ is a chamber-specific factor, which depends on the quality for which the absorbed-dose to water calibration factor was determined and the user's beam quality Q, as specified by R_{50} (where R_{50} is the depth at which the electron absorbed dose falls to 50% of the maximum dose in a beam with field size $\geq 10 \times 10$ cm^2 on the phantom surface), and P_{gr}^Q is required only for cylindrical ion chambers. It corrects for gradient effects at the reference depth. The $k_{R_{50}}$ factor is defined as:

$$k_{R_{50}} = k'_{R_{50}} k_{\mathrm{ecal}} \quad (3)$$

Where the photon-electron conversion factor, k_{ecal} is fixed for a given chamber model and is just $k_{R_{50}}$ for an electron beam of quality Q_{ecal}, that is, the value required to convert $N_{D,w}^{60Co}$ into $N_{D,w}^{Q_{\mathrm{ecal}}}$ the absorbed-dose calibration factor in an electron beam of quality Q_{ecal}. The electron beam quality conversion factor $k'_{R_{50}}$ converts $N_{D,w}^{Q_{\mathrm{ecal}}}$ into $N_{D,w}^{Q}$ for any beam quality Q. Therefore, in an electron beam, the absorbed-dose to water is given by:

$$D_w^Q = \mathrm{M} P_{\mathrm{gr}}^Q k'_{R_{50}} k_{\mathrm{ecal}} N_{D,w}^{60Co} \quad (4)$$

For the calibrations, the ion chamber was positioned inside the water phantom at a reference depth of 10 cm for the photon beams. For the electron energies, the reference depth was $0.6R_{50} - 0.1$ cm, and the calculated depths ranged from 1.3–6.0 cm. For each photon and electron beam irradiation, 100 MU were setup for a 10×10 cm^2 field at 100 cm source-to-phantom surface distance (SSD). Full details of the calibration procedure are given in the protocol [28].

2.2. Quality Assurance Tests for Independent Verification of Radiation Doses

The mailed TLD dosimetry irradiation systems based on the American Radiological Physics Center (RPC) technique were used to check the output of the two photon beams and three electron energies (6 MeV, 9 MeV and 12 MeV). The TLD dosimetry system comprised an acrylic mini-phantom loaded with TLDs (Figure 1(a)). Details about the TLD system including its calibration have been described [22]. The system is based on TLD-100 (LiF:Mg, Ti) powder package into cylindrical Teflon capsules filled with 20–22 mg of crystal. It is calibrated based on the signal-to-noise conversion established with reference dosimeters in a Co-60 beam, using a reference dose of 3 Gy. An uncertainty of 1.3% in the dose determination allows for a tolerance of ±5% to be used. For each beam being monitored, a separate system is mailed. Beam output was monitored at the depth of maximum dose, d_{max}, and for each beam setup, the dosimetry system was irradiated to a dose level of 3 Gy using a field size of 10×10 cm^2 at 100 cm SSD. Electron percent depth dose (PDD) measurements were also performed at various depths.

The full end-to-end test was achieved by requesting, imaging, and treating the RPC's MD Anderson anthropomorphic head and neck (H & N) phantom using an IMRT technique on our linac. Shown in Figure 1(b) is a photo of the MD Anderson IMRT H & N phantom. The humanoid phantom incorporates a dosimetry insert at specific positions and a radiochromic film insert. The insert consisted of one primary PTV containing four TLD capsules, a secondary PTV and an organ at risk (OAR), each containing two TLD capsules which provided point dose data for comparison. Three sheets of Gafchromic™ films provided dose profiles through the centre of the primary PTV. The Varian Eclipse treatment planning system (TPS) that uses the Analytical Anisotropic Algorithm (AAA) was used to generate a 6-MV IMRT treatment plan that meets specific objectives as defined. The treatment plan covered at least 95% of the primary PTV with a dose of 6.6 Gy, and at least 95% of the secondary PTV with 5.4 Gy. The plan restricted the dose to the OAR to less than 4.5 Gy. The generated IMRT plan was transferred and delivered on the 21EX linac where the entire phantom including the inserts was setup and then irradiated as if it were an actual patient.

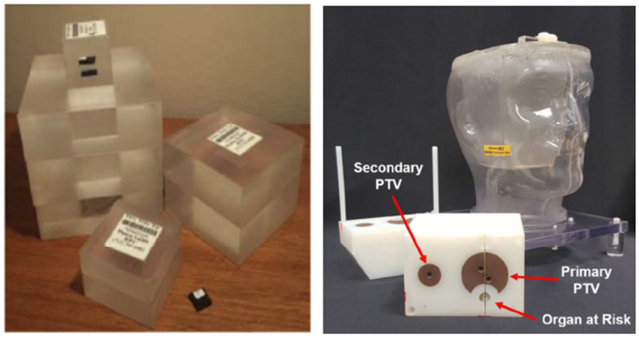


Figure 1. *(a) TLD dosimetry irradiation system comprising acrylic mini-phantom housing TLD dosimeters; (b) MD Anderson IMRT H&N anthropomorphic phantom for end-to-end test.*

The irradiated dosimetry systems including the entire anthropomorphic phantom and the inserts were then sent back to the Radiation Dosimetry Services of MD Anderson Cancer Center (MDACC) in the USA for dosimetric analysis. The mailed program reports the dose detected to the dose reported by our institution. For beam output measurements, agreement of the TLD dose ratio to within ±5% is considered a satisfactory check for the dose at d_{max}. For PDD measurements, agreement to within ± 0.5 cm is acceptable. The MDACC calculation of dose is based on the TG-51 protocol [28]. The criteria established by the Imaging and Radiation Oncology

Core Houston (IROC–H, formerly, the RPC) for the end-to-end test requires that our institution's treatment plan agrees within ±7% of measured TLD doses in the PTVs, and that that ≥ 85% of pixels pass ±4 mm distance-to-agreement (i.e., 7%/4 mm gamma analysis for film) in the high dose gradient area between the PTV and the OAR. That is, a gamma (γ) index analysis compared 2D dose distributions between film measurements and Eclipse TPS dose calculations [29–33]. The gamma analysis method evaluates the coincidence between measured and calculated dose distributions by using percentage dose difference (DD) and distance-to-agreement (DTA) where the evaluation criteria were set at 7%/4 mm (i.e., 7% DD and 4 mm DTA). From the analysis, the γ passing rate (i.e., the percentage of dose points with $\gamma < 1$) was calculated.

3. Results

3.1. Absolute Calibrations

Table 1 shows the results of machine calibration where the output (absorbed dose to water at d_{max}) of the linac is shown for each photon beam, and electron energy.

Table 1. *Absolute calibrations of the photon and electron beams at the depth of maximum dose.*

Output of photon beams (Gy per 100 MU)		Output of electron energies (Gy per 100 MU)				
6 MV	18 MV	6 MeV	9 MeV	12 MeV	15 MeV	18 MeV
0.999	1.004	0.999	1.002	0.997	0.998	0.999

3.2. Beam Output Measurements

Table 2 shows the results of TLD irradiations for monitoring the output of the 21EX linac for the two photon beams and three electron energies at d_{max}. Likewise, displayed in Table 3 are the PDDs obtained from TLD irradiations for monitoring the output of the linac for electron beams at depth.

Table 2. *Measured TLD doses for monitoring the output of photon and electron beams at the depth of maximum dose.*

Beam energy	Absorbed dose to water (Gy)		Ratio of MDACC to COC (MDACC/COC)
	Delivered by COC	Measured by MDACC	
6 MV photons	3.0	2.90	0.97
18 MV photons	3.0	2.90	0.97
6 MeV electrons	3.0	3.02	1.01
9 MeV electrons	3.0	2.95	0.98
12 MeV electrons	3.0	2.96	0.99

Table 3. *TLD percent depth dose measurements for monitoring electron beam output at depth.*

Energy (MeV)	TLD depth (cm)	MDACC measured PDD (%)	COC's depth at this PDD (cm)	Difference between MDACC depth and COC depth (cm)
6	2.0	76.8	1.9	0.1
9	3.3	62.9	3.4	–0.1
12	4.7	64.6	4.7	0.0

3.3. End-to-End Test for IMRT

Displayed in Table 4 is a summary of TLD results for IMRT phantom irradiation showing the measured radiation doses in the primary PTV, secondary PTV and organ at risk in various directions including the superior (sup.), anterior (ant.), posterior (post.), and inferior (inf.) directions.

Table 4. *Summary of TLD results for IMRT head and neck phantom irradiation.*

TLD location	TLD measured dose (Gy)	COC mean dose (Gy)	IROC-H vs COC (Measured/COC)	IROC–H's Criteria	Acceptable
Primary PTV sup. ant.	6.35	6.59	0.96	0.93–1.07	Yes
Primary PTV inf. ant.	6.35	6.64	0.96	0.93–1.07	Yes
Primary PTV sup. post.	6.52	6.77	0.96	0.93–1.07	Yes
Primary PTV inf. post.	6.49	6.74	0.98	0.93–1.07	Yes
Secondary PTV sup.	5.35	5.48	0.96	0.93–1.07	Yes
Secondary PTV inf.	5.31	5.47	0.97	0.93–1.07	Yes
Organ at risk sup.	2.99	2.95	1.01	0.93–1.07	Yes
Organ at risk inf.	2.87	2.85	1.01	0.93–1.07	Yes

Figures 2–4 show dose profiles through the centre of the primary PTV in various directions obtained using film measurements and TPS calculations (institution values).

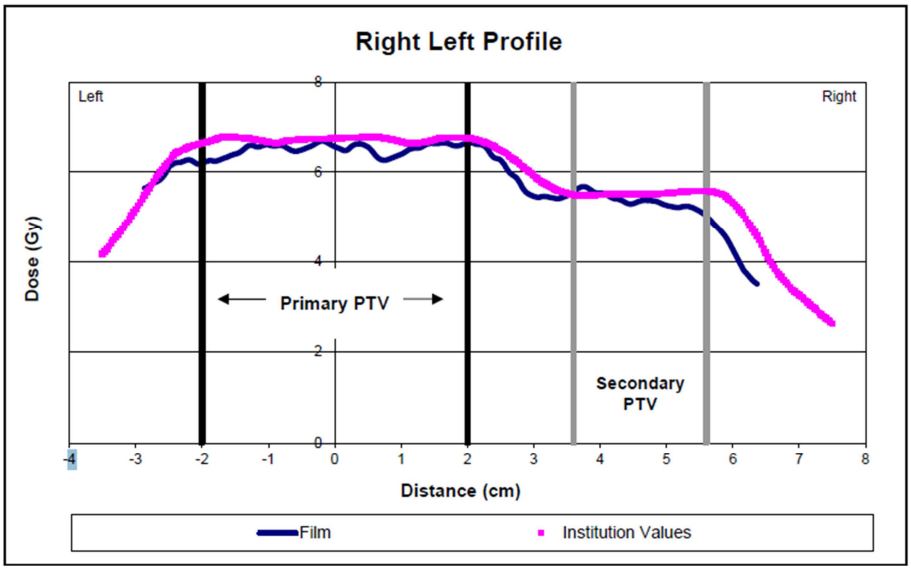


Figure 2. *Plot of right–left film profile through the primary PTV.*

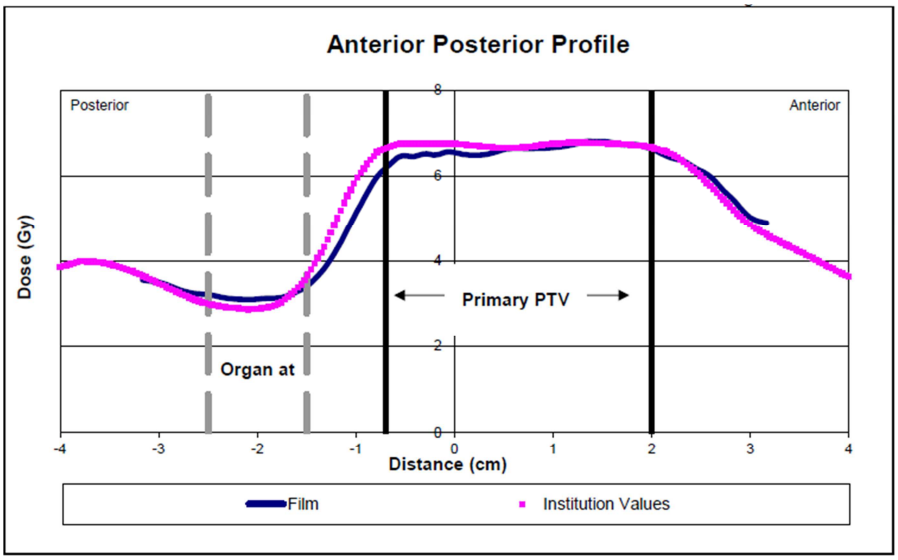


Figure 3. *Plot of anterior–posterior film profile through the primary PTV.*

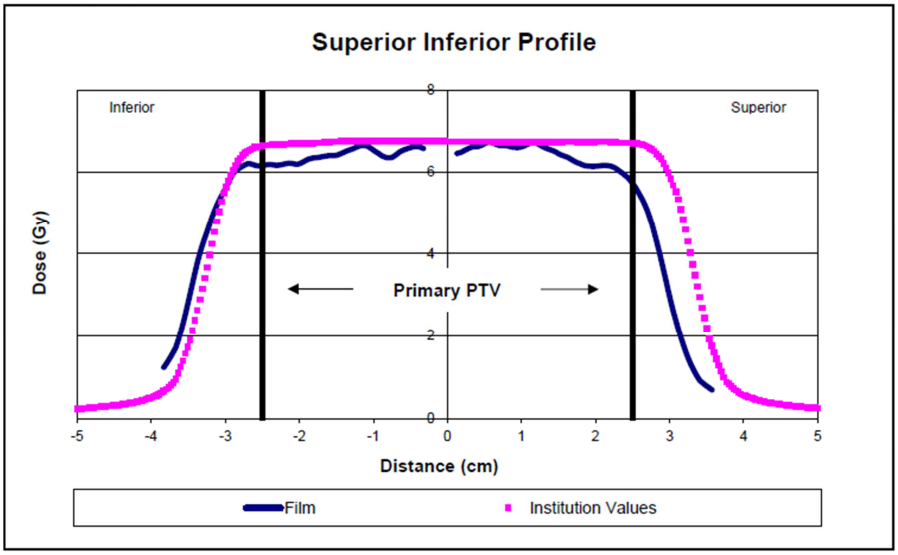
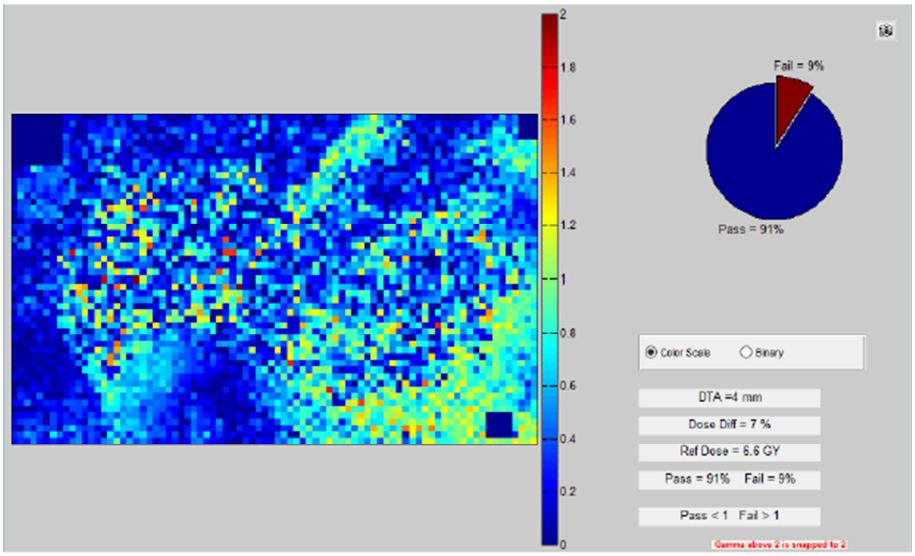
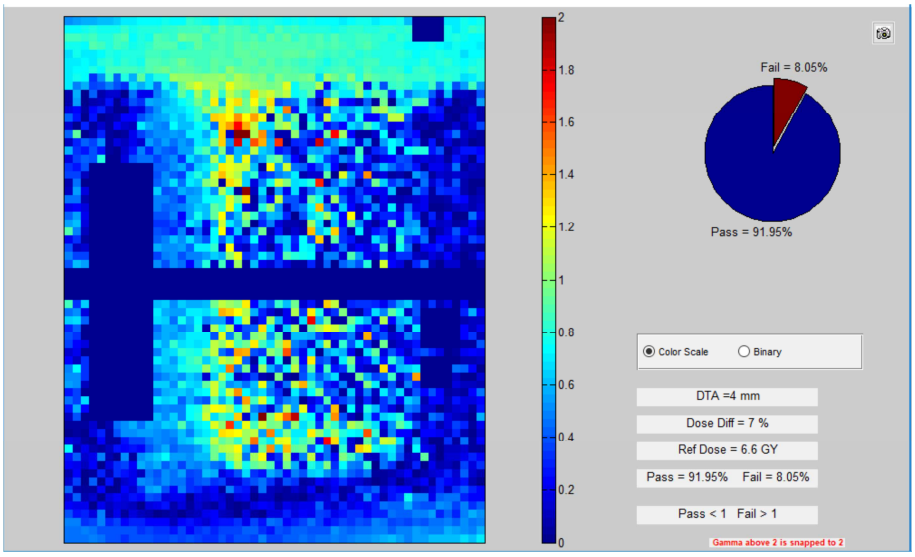


Figure 4. *Plot of a superior–inferior film profile through the primary PTV.*

Figures 5 (a) and (b) show gamma maps for the comparison of film measured and TPS calculated 2D dose distributions for IMRT head and neck phantom irradiation. Artifacts in the film image have been masked and are not included in the γ-analysis. Pie charts show the percentage of pixels passing and failing the specified gamma index evaluation criteria of 7%/4 mm.



(a)



(b)

Figure 5. *Gamma (γ) maps for the comparison of film and TPS 2D dose distributions for IMRT head and neck phantom irradiation. The figure shows the results of (a) axial γ-analysis (colour scale), and (b) sagittal γ-analysis (colour scale) using the area of axial/sagittal film and the corresponding area in the axial/sagittal plane from the TPS for the γ analysis. The colour palette shows the γ values.*

4. Discussion

To avoid disasters and inadequate dosimetric procedures that can have a quantifiable effect on clinical outcome in RT, patient safety should start with independent QA procedures. Prior to conducting the quality audit, our medical linac was properly calibrated to deliver 1.0 Gy per 100 MU as presented in Table 1. In Table 2, a comparison of beam output measurements at d_{max} made by MDACC with dose values delivered by COC shows that the results of TLD irradiations met the required criteria within ±3%. In Table 3, the depth of a given electron energy PDD measured by MDACC is compared with the depth stated by COC using absolute differences. The table shows that for electron output at depth, the differences in depth between MDACC measurements and COC values were within ±0.1 cm in agreement with the ±0.5 cm acceptable criteria for TLD at depth. For the end-to-end QA test, Table 4 shows that the ratios of MDACC TLD measured to COC delivered mean doses ranged between 0.96 and 1.01, which are within the required range from 0.93–1.07. Shown in Figures 2–4 are dose profiles through the centre of the primary PTV comparing film measurements (MDACC) and TPS calculations (institution (= COC values)). Gamma maps for the comparison of 2D dose

distributions between film and TPS shown in Figure 5 depict that the gamma pass rate is ≥ 91%. Therefore, the results for the end-to-end test show that our institution's IMRT treatment plan satisfied the passing criteria of ±7% of measured TLD doses in the PTVs, and ≥ 85% of pixels passed ±4 mm DTA (i.e., 7%/4 mm gamma analysis for film) in the high dose gradient area between the PTV and the OAR.

The MD Anderson anthropomorphic H&N phantom is generally used to credential institutions wishing to participate in National Cancer Institute–sponsored clinical trials employing IMRT delivery techniques [24, 34]. The H&N phantom irradiation results presented in this study do meet the credentialing criteria established by the Imaging and Radiation Oncology Core Houston. That is, had it been COC was applying for credentialing to enter patients into certain protocols that allow the use of IMRT, COC would have satisfied the phantom irradiation component of the credentialing process. Noting that about 30% of institutions in the USA usually fail the dosimetric QA tests [24, 34], COC has achieved a milestone by passing the tests. Therefore, the end-to-end test which verified the whole accuracy of the RT process using a humanoid phantom indicated that COC can provide high quality radiation treatments to cancer patients using advanced treatment techniques to deliver a lethal radiation dose to malignant tissues to provide a high probability of tumour control while sparring or inducing minimal damage to adjacent normal tissues and organs at risk. For example, during pelvic irradiation in the case of prostate or cervical cancer, we must minimize the radiation dose to structures such as the rectum and bladder while maximizing the dose to the prostate/cervix which contains the tumour.

At COC, we face various challenges in the delivery of high quality RT. Some of the major challenges include unreliable and unstable power and internet. In the first year of operations, about 35% of our expenses went for power expenses (electricity bills and purchase of fuel when utility power is unavailable). In addition, the internet bandwidth paid for is not what is supplied and the internet bandwidth is very unstable. Transmission of large files is not problematic but stability of the network to enable contouring operations from Cameroon for 3D and IMRT based planning is not feasible presently. Moreover, we faced difficulties to transport the humanoid phantom from the USA to Cameroon. We approached FedEX and DHL to transport the phantom; after scanning it, both companies refused to transport it on the pretext that there could be a bomb planted inside it. We even requested the RPC to send an invoice directly to FedEx to courier the phantom but FedEX refused. Finally, we had to arrange with someone to travel with it from the USA to Cameroon and from Cameroon back to the USA. In spite of various challenges that inhibit the implementation of RT in SSA including the lack of the necessary funds and expertise, we adopted a hybrid tele-radiotherapy system using telemedicine protocols that has enabled us to provide high quality care in oncology that would not have been possible. The oncology telemedicine model consists of a team of US-based experts supported by an onsite Cameroon-based team.

5. Conclusion

The independent dosimetry audit presented in this work is of value to radiotherapy centres in resource-limited regions to ensure the provision of safe and high-quality radiotherapy. The quality audit verified that the radiation equipment at COC has been correctly commissioned for clinical implementation. It verified the accuracy of our treatment unit calibration, and the entire accuracy of the RT process. By satisfying the MD Anderson humanoid phantom irradiation criteria usually used for credentialing institutions to assure quality and safety of complex radiation treatments, we have demonstrated that we can implement complex radiotherapy techniques to shape the radiation doses around critical structures, minimizing the dose to surrounding healthy tissues and organs at risks while maximizing the doses to tumours. Therefore, despite the various challenges that impede the operation of RT facilities in SSA, COC has demonstrated that it is feasible to implement advanced radiotherapy programs based on linac technology in a resource-constrained region.

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