Physica Medica 65 (2019) 128–136

Contents lists available at ScienceDirect

Physica Medica

journal homepage: www.elsevier.com/locate/ejmp

IMRT national audit in Portugal

Tania Santos[a,b,*], Maria do Carmo Lopes[b], Eduard Gershkevitsh[c], Filipa Vinagre[d], David Faria[e], Liliana Carita[f], Miguel Pontes[g], Sandra Vieira[h], Esmeralda Poli[i], Sofia Faustino[j], Filipa Ribeiro[k], Mauro Trindade[l], Fernanda Ponte[m], Carlos Marcelino[n], Cláudio Batista[o], Susana Oliveira[p], Rita Figueira[q], Joana Lencart[r], Ester Gallego Diaz[s], Katia Jacob[t], Sandra Brás[u], Rui Pirraco[v], Joanna Izewska[w]

[a] Departamento de Física, Universidade de Coimbra, Coimbra, Portugal
[b] Serviço de Física Médica, IPOCFG, E.P.E., Coimbra, Portugal
[c] North Estonia Medical Centre, Tallinn, Estonia
[d] CHUC, E.P.E., Coimbra, Portugal
[e] Lenitudes Medical Center and Research, Sta Maria da Feira, Portugal
[f] IPOLFG, E.P.E., Lisboa, Portugal
[g] JCS – Centro Oncológico Dra Natália Chaves, Carnaxide, Portugal
[h] Fundação Champalimaud, Lisboa, Portugal
[i] CHULN-Hospital de Sta Maria, Lisboa, Portugal
[j] Hospital da Luz, Lisboa, Portugal
[k] CHBM, E.P.E., Barreiro, Portugal
[l] CHTMAD, E.P.E., Vila Real, Portugal
[m] Instituto CUF Porto, Porto, Portugal
[n] Lenicare, Évora, Portugal
[o] JCS – Clínica de Radioncologia de Santarém, Santarém, Portugal
[p] JCS – Clínica de Radioncologia do Algarve, Faro, Portugal
[q] CHUSJ, E.P.E., Porto, Portugal
[r] IPOPFG, E.P.E., Porto, Portugal
[s] JCS – Clínica de Radioncologia da Madeira, Madeira, Portugal
[t] Hospital CUF Descobertas, Lisboa, Portugal
[u] JCS – Clínica de Radioncologia Madalena Paiva, Açores, Portugal
[v] Hospital de Braga, Braga, Portugal
[w] Dosimetry and Medical Radiation Physics Section, International Atomic Energy Agency, Vienna, Austria

ARTICLE INFO

Keywords:
Intensity modulated radiation therapy
On-site dosimetry audit
Head and neck treatment

ABSTRACT

Purpose: The IAEA newly developed "end-to-end" audit methodology for on-site verification of IMRT dose delivery has been carried out in Portugal in 2018. The main goal was to evaluate the physical aspects of the head and neck (H&N) cancer IMRT treatments. This paper presents the national results.

Methods: All institutions performing IMRT treatments in Portugal, 20 out of 24, have voluntarily participated in this audit. Following the adopted methodology, a Shoulder, Head and Neck End-to-End phantom (SHANE) – that mimics an H&N region, underwent all steps of an IMRT treatment, according to the local practices. The measurements using an ionization chamber placed inside the SHANE phantom at four reference locations (three in PTVs and one in the spinal cord) and an EBT3 film positioned in a coronal plane were compared with calculated doses. FilmQA Pro software was used for film analysis.

Results: For ionization chamber measurements, the percent difference was within the specified tolerances of ± 5% for PTVs and ± 7% for the spinal cord in all participating institutions. Considering film analysis, gamma passing rates were on average 96.9% ± 2.9% for a criterion of 3%/3 mm, 20% threshold, all above the acceptance limit of 90%.

Conclusions: The national results of the H&N IMRT audit showed a compliance between the planned and the delivered doses within the specified tolerances, confirming no major reasons for concern. At the same time the audit identified factors that contributed to increased uncertainties in the IMRT dose delivery in some institutions resulting in recommendations for quality improvement.

* Corresponding author at: Serviço de Física Médica, IPOCFG, E.P.E., Avenida Bissaya Barreto, 3000-075 Coimbra, Portugal.
E-mail address: taniafssantos@gmail.com (T. Santos).

https://doi.org/10.1016/j.ejmp.2019.08.013
Received 22 March 2019; Received in revised form 25 July 2019; Accepted 15 August 2019
Available online 23 August 2019

1. Introduction

Intensity modulated radiation therapy (IMRT), including volumetric modulated arc therapy (VMAT), has become a standard treatment technique given the associated benefits [1]. However, in comparison to 3-dimensional conformal radiotherapy (3D-CRT), IMRT is more demanding in both planning and delivery, requiring a strict quality assurance (QA) program. As a complement, many international organizations [2–8], including the International Atomic Energy Agency (IAEA), recommend that every institution that intends to introduce such complex techniques in clinical practice should participate in an independent dosimetry audit.

The IAEA has a vast experience in promoting dosimetry audits in radiotherapy to its Member States, involving both postal services and on-site visits. A postal audit program has been conducted in collaboration with the World Health Organization (WHO) to check the calibration of high energy photon beams for 50 years now [9]. The methodology for a national on-site end-to-end audit of 3DCRT treatment techniques using an anthropomorphic thorax phantom [10] was developed by the IAEA in 2008. This audit has been carried out in eight countries in Europe [11], including Portugal [12]. With the introduction of IMRT/VMAT in clinical practice, development of audit procedures to ensure the safe use of this technique became necessary. Thus, some methodologies have already been established and used at a national/regional level [7,13–17] or on a large scale [18–21]. An independent audit of the local patient-specific QA systems has been recently conducted in the Netherlands [14] where the same set of predefined IMRT/VMAT clinical plans was considered in all institutions for dose computation. In about 20% of the evaluated measurements, the results of audit and the local QA were in disagreement. The Radiological Physics Center (RPC) in Houston (now called Imaging and Radiation Oncology Core, IROC – Houston QA Center) has implemented a remote program for clinical trials credentialing of Head and Neck (H&N) IMRT treatments, using a semi-anthropomorphic phantom [19]. Thermoluminescent dosimeters (TLD) and radiochromic film are used to assess the agreement between the calculated and measured doses. The current acceptability criteria is ± 7% dose difference for TLD and a passing rate of 85% in global gamma analysis (7% dose difference/4 mm distance-to-agreement) for film. Significant improvements in the results have been achieved over the years, but still about 10% of the irradiations fail to meet the tolerances [22].

In large scale settings with several hundred facilities to be audited, remote audits are typically preferred due to their cost-effectiveness. As part of a multi-step remote audit system, the IAEA has disseminated a methodology for postal end-to-end IMRT/VMAT audits using TLDs and film in a specially developed solid phantom that is being implemented by some national dosimetry audit networks [23]. However, on-site visits have demonstrated advantages over remote postal audits – results are typically available without delay and any issues or discrepancies can be discussed between the auditor and the auditee, and possibly resolved during the visit; more detailed observations can be made e.g. regarding phantom positioning and the performance of local QA as well as the overall process of IMRT delivery at the institution. Usually, postal audits are more restricted in terms of the audit scope and program, whereas on-site visits allow more flexibility, e.g. additional modalities or delivery techniques can be audited as needed and if time allows. As main drawbacks, on-site visits involve substantial travel costs and the auditor's time.

Recognizing the complexity associated with the IMRT procedures and being aware of the advantages of on-site visits in some national settings, the IAEA has recently developed a national audit program to review the physics aspects of H&N IMRT treatments, following an end-to-end approach [24]. A specially designed anthropomorphic phantom named *Shoulder, Head and Neck End-to-End* (SHANE – Computerized Imaging Reference Systems (CIRS) Inc., Norfolk, Virginia, USA) [25] and a DICOM set of pre-defined contours are used to represent a patient with a nasopharynx tumour. The leading objective of the audit is to verify on-site that the complete radiotherapy treatment chain from computed tomography (CT) scanning to dose delivery leads to the desired results within the defined tolerances. The feasibility of the methodology was verified through a multicentre pilot study in a variety of clinical settings and the feedback by participants was carefully considered to fine-tune it [26]. This audit has been carried out in Portugal in 2018 with the IAEA assistance. The Medical Physics Division of the Portuguese Physics Society was designated the national auditing organization and Instituto Portugues de Oncologia Coimbra (IPOCFG, E.P.E.) the pilot centre. The national experience and results are presented in this paper.

2. Materials and methods

2.1. National characterization

In Portugal, in 2018, there were 24 radiotherapy institutions equipped with 55 treatment machines including, 52 linear accelerators (linacs), one Tomotherapy, one Cyberknife and one Gamma Knife. By the time of the audit, twenty institutions had already introduced IMRT in clinical practice, with 14/20 having more than 2 years of experience in H&N IMRT. IMRT treatments represented about one third of the total external beam radiotherapy treatments in the country. H&N patients corresponded on average to 20% of the total number of patients treated with IMRT.

All 20 institutions voluntarily participated in the audit with one equipment set (linac/TPS) and IMRT technique. The treatment units comprised 19 linacs (14 Varian and 5 Elekta) and one Tomotherapy. From these, 14 treatment machines were less than 10 years old and 10 of them had been installed in the past 5 years. The oldest linac had more than 15 years. Regarding the nominal beam energy, 18/20 institutions used 6 MV and two 6FFF MV (Tomotherapy and one linac). The IMRT delivery techniques were: volumetric modulated arc therapy – VMAT (15), sliding window (3), step & shoot (1) and helical IMRT (1). The treatment planning systems included 13 Eclipse (Varian), 5 Monaco (Elekta), 1 XiO (Elekta) and 1 VoLO (Accuray). And finally, the dose calculation algorithms were: AAA (12), AcurosXB (1), Monte Carlo (5), fast superposition (1), and CCC superposition (1). Dose calculation grid resolution varied between 1 and 3 mm: 1 mm (1), 2 mm (5), 2.5 mm (11) and 3 mm (3).

2.2. Audit phases

Before starting the audit program, a kick-off workshop was organized at the pilot centre to present the adopted methodology and discuss its implementation. The project encompassed different phases that are described in the following subsections.

2.2.1. Pre-visit activities

Some pre-visit activities were required to be performed by the participating institutions prior to the on-site visit. Aiming at speeding up the treatment planning phase, each institution had to create a preliminary IMRT plan based on a pre-visit CT dataset of the SHANE phantom and the corresponding pre-delineated structures, provided by the IAEA. The structures set included three planning target volumes (PTV_7000, PTVn1_6000 and PTVn2_5400) and four organs-at-risk (spinal cord, brainstem, left parotid and right parotid). For treatment planning, each institution considered the local treatment technique and their typical calculation specifications for H&N (dose calculation algorithm, grid resolution, inclusion of the treatment couch, etc.). To guide the optimization process, dose-volume constraints were provided (Table S1 – Supplementary data). In addition, participants were asked to calculate on their TPS, output factors (OF) for 5 MLC-shaped fields ($10 \times 10\,cm^2$, $6 \times 6\,cm^2$, $4 \times 4\,cm^2$, $3 \times 3\,cm^2$ and $2 \times 2\,cm^2$) to compare with the IROC-Houston QA Centre's reference dataset [27,28].

Tolerances of ± 3% for the 2 × 2 cm^2 field and ± 2% for larger fields were considered [23]. Inplane and crossplane profiles for a MLC-shaped 2 × 2 cm^2 field (at SAD = 100 cm, depth = 10 cm) were also calculated in the TPS. Field sizes (defined as the normalized dose profile FWHM) and penumbra widths (20–80%) were recorded.

2.2.2. Pilot centre audit

The audit at the pilot centre was performed in the presence of an IAEA expert at the Tomotherapy unit. Before the SHANE irradiations, a dose comparison was done between the IAEA calibrated ionization chamber and a pilot centre's dosimetry system composed of a TM31010 Semiflex 0.125 cc ionization chamber and UNIDOS E electrometer (PTW-Freiburg, Germany) in the machine specific reference conditions for Tomotherapy [29]. This aimed at ensuring the metrological quality of the pilot centre's dosimetry system so that it could be used for audit measurements at participating centres. The result of the dose comparison was within 0.2%.

2.2.3. On-site visits

Following the IAEA audit methodology, the national auditor travelled through the institutions with the phantom, the audit dosimetry system, a barometer, a thermometer and a box with Gafchromic EBT3 (Ashland Inc., Covington, Kentucky, USA) films from a single batch, appropriately cut, numbered and marked. All on-site measurements were performed using the audit dedicated equipment. After each visit, the equipment integrity and long-term stability of the dosimetry system composed by the ionization chamber and electrometer were checked.

Each on-site visit took two days, the first for phantom scanning and treatment planning and the second for dose measurements.

a) CT scan of the SHANE phantom

The on-site visit started by performing a CT scanning of the SHANE phantom – on-site planning CT set – following the local CT scanning protocol for H&N patients. The phantom was positioned on the couch and aligned without using any immobilization devices such as head rests or thermoplastic masks as per the audit instructions. In the shoulders region of SHANE phantom seven reference materials are embedded – lung inhale, lung exhale, water vial, soft tissue, spinal cord, trabecular bone and cortical bone – with certified relative electron density (RED)/mass density values. After transferring the on-site planning CT set to the local TPS, a CT to RED/mass density curve was built to be compared with the one stored in the TPS [24]. Differences between curves of ± 5 HU for water and ± 20 HU for all other materials were considered acceptable, as per the IAEA TRS-430 recommendations for TPS verification [30].

b) Treatment planning phase

The pre-visit CT set was co-registered with the on-site planning CT using rigid registration and the structures were copied over. The volume of each delineated structure was checked against a reference set of expected volume values, provided by the IAEA, to ensure that no major changes had occurred. The adopted tolerances were established based on the analysis of data resulting from a multicentre study to test the feasibility of the treatment planning exercise [31]. The pre-visit plan was then transferred (copied or saved as template) to the on-site planning CT set and re-optimized. The provided set of contours included four structures that represented the ionization chamber volume surrogating the measurement reference points. The mean dose over those structures was registered.

Patient-specific QA of the IMRT created plan was performed by the local medical physics team using their equipment, analysis metrics, and acceptability criteria as for a typical H&N cancer patient. Some institutions considered more than one verification method. A summary of the used systems is presented in Table 1.

c) On-site measurements

The on-site measurements were performed on the second day. Besides the dosimetric verification of the newly created H&N IMRT plan, measurements also included: i) a test to evaluate MLC performance; ii) irradiation of an EBT3 film with a 2 × 2 cm^2 MLC-shaped field as configured in the pre-treatment phase; iii) beam output verification; iv) irradiation of dose reference strips for film calibration, along with verification using the audit dosimetry system. The MLC test used either Electronic Portal Imaging Device (EPID) or film, considering an irradiation pattern as per IAEA specifications (5 strips of all MLC length, 3 cm gap between strips and the minimum achievable leaf opening). Film was placed isocentrically on a solid slab phantom (SAD = 100 cm) with at least 2 cm of build-up. EPID was positioned as close as possible to the isocenter.

Daily output of the machine was checked against the reference dose calibration modelled in the TPS (10 × 10 cm^2 field, SAD = 100 cm, depth = 10 cm) with the audit dosimetry system. The measured dose was determined according to the TRS 398 [32] dosimetry protocol and compared with the calculated dose as follows:

$$Deviation\ [\%] = 100 \times (D_{cal} - D_{meas})/D_{meas} \quad (1)$$

where D_{cal} is the TPS calculated and D_{meas} is the measured dose. A tolerance of ± 2% was considered.

Dosimetric verification of the created H&N IMRT treatment plan was done through ionization chamber measurements performed using the audit dosimetry system and EBT3 film irradiation. The ionization chamber was positioned in one of the four measurement reference locations, and at least two irradiations were performed per reference point. The calculated and measured doses were compared using Eq. (1) but taking D_{cal} as the corrected calculated dose for daily output variation – D_{cal^*}. The established tolerances were ± 5% for PTVs and ± 7% for the spinal cord [26]. An EBT3 film was then placed in a coronal

Table 1
Local verification systems used to validate the H&N IMRT audit plan.

System	Manufacturer	No. of institutions
Image detector dosimetry	EPID dosimetry (Varian Medical Solutions, Palo Alto, CA, USA); Dosimetry Check (LifeLine Software Inc., Austin, TX, USA)	8
MatriXX	IBA Dosimetry, Schwarzenbruck, Germany	4*
ArcCHECK	SunNucelar Corporation, Melbourne, FL, USA	4
Octavius II + PTW 729 array	PTW-Freiburg, Germany	1
Octavius 4D + PTW 1500 array + ionization chamber measurements	PTW-Freiburg, Germany	3
EBT3 film + ionization chamber measurement	Ashland Inc., Covington, Kentucky, USA	2
Ionization chamber measurements		2**
Independent MU/dose calculation	RadCalc (LifeLine Software Inc., Austin, TX, USA); Mobius3D (Varian Medical Solutions, Palo Alto, CA, USA)	3

* In 1 institution the MatriXX array was used in combination with a slab phantom and in 3 with MultiCube; in one of them it was also attached to the gantry head, and COMPASS software was used to reconstruct 3D dose.

** Ionization chamber measurement in combination with slab solid water phantom.

Table 2
Summary of the relative difference between OFs calculated by TPS and reference dataset.

	Field size (cm × cm)			
	6 × 6	4 × 4	3 × 3	2 × 2
Overall (N = 18)				
Mean	0.1%	0.6%	1.4%	2.1%
Standard deviation (SD)	0.6%	0.6%	0.7%	0.9%
N exceeding the tolerance	–	–	3	4
Varian linac – Eclipse TPS (N = 12)				
Mean	0.1%	0.9%	1.6%	2.3%
Standard deviation	0.1%	0.3%	0.4%	0.7%
N exceeding the tolerance	–	–	2	3
Elekta linac – XiO/Monaco TPS (N = 5)				
mean	−0.5%	−0.2%	0.6%	1.2%
standard deviation	0.5%	0.5%	0.5%	0.8%
N exceeding the tolerance	–	–	–	–

plane of SHANE and given three treatment fractions as per IAEA methodology [24]. After measurements with SHANE, the reference strips were irradiated for film calibration.

d) Post-visit analysis

All films irradiated during the on-site visit were analysed centrally by the national auditing team at the pilot centre. Calibration and measurement films were scanned at least 48 h after irradiation using a flatbed scanner Epson Expression 10000 XL (Seiko Epson Corporation, Japan). To guarantee a stabilized scanner response, 16 empty scans were performed after a warm-up time of at least 30 min. A glass compression plate was put on films top to ensure film flatness. RGB images were acquired in transmission mode, at 48 bits colour depth, 72 dpi, landscape orientation and with all colour corrections turned off.

For EBT3 film calibration, 10 strips were irradiated to known doses (0, 1, 2, 3, 4, 5, 6, 7, 8 and 9 Gy) in reference conditions (10 × 10 cm^2 field, SAD = 100 cm, depth = 10 cm) in a 6 MV photon mode at the pilot centre. A calibration curve for each channel (red, green and blue) was obtained from the average pixel values of a central region of interest of 1 × 1 cm^2.

For audit films processing, the conversion from pixel values to dose was performed using the generic calibration curve updated by two reference strips at zero dose and 110% over the maximum TPS calculated dose in the film plane (irradiated in each institution) [33]. The agreement between the film dose distribution and TPS calculated dose was evaluated with FilmQA Pro software (Ashland Inc., Covington, Kentucky, USA) using triple channel dosimetry, mimicking IAEA practice [23,26]. 2D global gamma analysis was performed, with normalization done to a high dose low gradient region. The tolerance limit was a gamma passing rate of 90%, for a criterion of 3% of global dose/3mm distance-to-agreement with 20% dose threshold [26]. TPS dose distribution was considered the reference, meaning that the film dose distribution was rescaled to the resolution of the TPS dose grid. To minimize the impact of grid size on gamma analysis, the calculated dose distribution in the film plane was exported with a resolution of about 1 mm in all institutions, where possible.

To investigate the correlation between ionization chamber (IC) dose differences and gamma passing rates for film analysis, an average percent deviation was calculated considering the four measurement points, as follows:

$$\frac{1}{4}\left[\left(\frac{|D^{*}_{cal}-D_{meas}|}{D_{meas}}\right)_{PTV\_7000}+\left(\frac{|D^{*}_{cal}-D_{meas}|}{D_{meas}}\right)_{PTVn1\_6000}+\left(\frac{|D^{*}_{cal}-D_{meas}|}{D_{meas}}\right)_{PTVn2\_5400}+\left(\frac{|D^{*}_{cal}-D_{meas}|}{D_{meas}}\right)_{SpinalCord}\right] \quad (2)$$

However, when using Eq. (2) the spinal cord is given the same weight as PTVs, ignoring that the corresponding measurement point is located in a low dose high gradient region. Therefore, in a second analysis, the last term (SpinalCord) of Eq. (2) was excluded from the average IC percent deviation.

The EBT3 films irradiated with the 2 × 2 cm^2 field after being scanned and converted to dose maps, were analysed with RIT113 software v5.1 (Radiological Imaging Technology Inc., Colorado Springs, CO, USA), the clinically used software at the pilot centre. The measured field size (defined as the normalized dose profile FWHM) and the penumbra width (20–80%) were compared with those calculated in the pre-visit phase. The tolerances were ± 2 mm for the field size and ± 3 mm for the penumbra width.

MLC tests performed on EPID were analysed using the freeware software *Pylinac* implemented as a web app (https://assuranceqa.herokuapp.com/). Films were analysed using the FilmQA Pro software. The maximum leaf bias and the median positioning error were checked. The tolerances were ± 1 mm for the maximum leaf bias and ± 0.5 mm for the median positioning error [34].

3. Results

3.1. Small field dosimetry and MLC performance tests

For the output factors calculated on TPS using 6 MV photon mode, the percent differences to IROC-Houston QA Centre's reference data [27,28] were determined. The average values are presented in Table 2 as a function of field size.

On average, the audited TPSs overestimated OFs in comparison to the reference IROC-Houston dataset. Nevertheless, the differences were generally within the tolerances, with three institutions having a deviation higher than 2% for 3 × 3 cm^2 field size and four exceeding the tolerance of 3% for the 2 × 2 cm^2 field.

The measured field size and the penumbra widths obtained from analysis of the film irradiated with a 2 × 2 cm^2 MLC-shaped field were compared with the ones calculated on TPS. Differences were within ± 2 mm for both the field size and penumbras in all institutions.

MLC performance test results were within ± 0.5 mm for the individual leaf pairs positioning bias in all institutions. The maximum positioning error was on average 0.19 ± 0.11 mm (maximum of 0.49 mm) and the average of the median bias was 0.05 ± 0.03 mm (maximum of 0.10).

3.2. CT to density conversion

The majority of institution's CT scanners were radiotherapy dedicated. All involved TPS had introduced a customised CT to RED/mass density conversion curve.

The on-site verification of CT to density conversion with SHANE revealed a general failure in trabecular bone (74%) and cortical bone (95%) reference materials. Some other discrepancies were noticed and corrected during the on-site visit, being the H&N IMRT plan calculated using the updated CT to density curve. In one institution, a difference of about 212 HU was observed in air as the first point of the curve introduced in TPS had a RED of 0.19; a data point corresponding to water was added in another institution as a discrepancy of 44 HU was revealed. A major correction was done in two institutions where the CT to RED curve was built using a combination of CIRS Head & Torso phantom (Model 002H9K) and CATPHAN (Model 600) corresponding reference materials. CAPTHAN is not a recommended phantom for this purpose but for CT number constancy check only [35]. The introduced curve on TPS had a shape as shown in Fig. 1 – "Cal 2016 CIRS Head & Torso + CATPHAN" which had not been noticed by the local medical physics team. Thus differences up to 239 in trabecular bone and 394 HUs in cortical bone reference materials were registered – "Cal 2018 CIRS SHANE". Data points corresponding to CATPHAN materials were

then removed and the resulting CT to RED curve – "Cal 2016 CIRS Head & Torso" – was similar to the one obtained on-site with SHANE, as can be seen in Fig. 1.

3.3. Treatment plans

The treatment planning exercise was considered challenging, although all but three created plans fulfilled PTVs coverage and organs-at-risk dose limits. Some characteristics of the H&N treatment plans related to the delivery technique are presented in Table 3.

From the 20 H&N IMRT plans, 15 were planned for VMAT, three sliding window, one step & shoot and one helical IMRT. Most institutions performing VMAT (10/15) used two arcs. All sliding window plans had 9 beams. A great difference (about 2 times, on average) in total number of MU between sliding window and VMAT plans was noticed as well as the large spread of total MUs of VMAT plans created in Eclipse. For VMAT plans, the number of control points (CP) per arc was constant (178) and always higher in Eclipse, while the number of CPs was variable in Elekta plans (ranging from 69 to 136). A huge difference was observed between the number of CPs per field for the sliding window plan created in Monaco to be delivered by a Varian linac (53.2) in comparison to plans created in Eclipse, for the same delivery machine type and technique (187.1 on average).

Pre-treatment verification of the created plans was performed as per local routine to evaluate its deliverability and acceptability of the QA results. All plans were considered deliverable and acceptable for treatment.

3.4. Output check

In most institutions, 17/20, the daily output of the machine was within the established tolerance of ± 2% from reference. The percent difference between calculated – 2 Gy – and measured doses using the audit dosimetry system was on average −0.6% ± 0.9% (1SD), varying from −2.4% to 0.8%. Beam output on the audit day was taken into account for the subsequent measurements of the SHANE phantom.

3.5. IMRT measurements in SHANE phantom

In total, 20 H&N IMRT plans were verified through ionization chamber measurements and EBT3 film irradiation. SHANE phantom was positioned on the treatment couch, and aligned with lasers. Phantom positioning was verified according to the local standard H&N image-guided radiation therapy (IGRT) method. Most of the institutions, 17/20 used kV CBCT, 1/20 used MV portal imaging, 1/20 MVCT and in one institution phantom alignment was done based on lasers only, as it was not possible to use the local IGRT method (MV portal imaging) due to technical problems.

Percent differences between the calculated doses corrected for the daily output variation and the ionization chamber measured doses at each reference point are presented in Fig. 2.

Differences were within the established tolerances of ± 5% for PTVs and ± 7% for spinal cord in all institutions, being below ± 3% in most of them. Average differences were −0.6 ± 2.0% (1SD) for the measurement point in PTV_7000, 0.4 ± 1.9% (1SD) in PTVn1_6000, −0.1 ± 2.0% (1SD) in PTVn2_5400 and 0.2 ± 2.2% (1SD) in spinal cord. A major deviation in the point measurement located in spinal cord was registered in one institution. The difference between calculated and measured dose was −12.7%. The high gradient together with the low calculated dose (mean of ~0.5 Gy/fraction) and plan complexity were the identified reasons for the deviation. A new treatment plan was created afterwards by the local team and a follow-up visit was arranged. The difference was totally resolved, and therefore the initial result was not shown in the graphs and it was excluded from the statistics.

Regarding film analysis, gamma passing rates were on average 96.9 ± 2.9% (1SD), ranging from 90.3% to 99.1%, all above the acceptance limit of 90% for a criterion of 3% global dose/3 mm, 20% threshold.

The correlation between ionization chamber measurements and film results was investigated using equation (2). As can be seen in Fig. 3a) there is clearly a group of institutions where higher gamma passing rates (> 95%) correspond to IC measurement results within 3%. When considering only PTVs, the separation between the two groups of institution results is even more evident – Fig. 3b). The group of institutions with higher gamma passing rates (> 95%) and even lower differences between the IC measured and TPS calculated doses (< 2%) is clearly separated from a group of institutions with poorer film and IC results. There is also a borderline result with a passing rate of 95.1% and IC result > 2% located in the upper right quadrant in Fig. 3b).

4. Discussion

A comprehensive audit programme developed by the IAEA to assess the quality of H&N IMRT treatments through on-site visits was implemented in Portugal. To overcome the audit running costs the kick-off workshop was organised with an attractive scientific program and technical exhibition which helped to raise the required funds.

The audit established methodology comprises the dosimetric verification of an H&N IMRT plan created by each participating institution, and a set of tests to evaluate small field dosimetry, MLC performance, the machine beam output and the CT numbers to RED/mass density conversion curve.

The modelling of small fields in TPS is one of most important steps to ensure IMRT dose calculation accuracy [36]. To verify its implementation, output factors were calculated for field sizes ranging from $2 \times 2\,cm^2$ to $6 \times 6\,cm^2$ and compared with reference data published by the IROC-Houston [27,28]. This comparison showed that the TPS tended to overestimate OF, being the deviations larger with decreasing field size. Moreover, differences for the $2 \times 2\,cm^2$ and $3 \times 3\,cm^2$ fields were higher in the Varian linac/Eclipse TPS group than in Elekta linac/XiO/Monaco TPS one. These results were in line with the findings of an IAEA multinational audit of calculated small field output factors that included data from more than 200 different beams [20]. The agreement between inplane and crossplane profiles for a $2 \times 2\,cm^2$ MLC-shaped field calculated in the TPS and the measured ones with EBT3 film was also evaluated. Both field size and penumbra widths were checked and differences were within ± 2 mm in all institutions. However, the agreement was less satisfying for the crossplane profiles, which may be explained by the modelling of the leaf

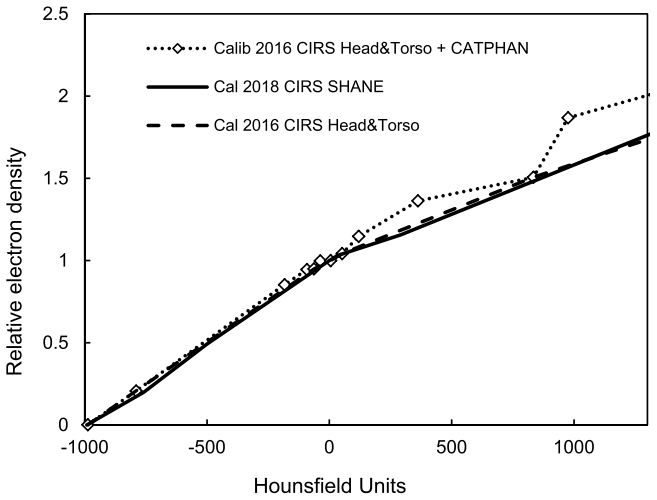

Fig. 1. Comparison between CT to RED conversion curves obtained with data from measurements carried out in 2016 and in the IMRT audit in one of the visited institutions.

Table 3
Treatment plans characteristics.

	Delivery technique		
	VMAT (N = 15)	Sliding Window (N = 3)	Step & Shoot (N = 1)
# Fields/Arcs	2 Arcs (N = 10) 3 Arcs (N = 2) 4 Arcs (N = 3)	9 fields (N = 3)	7 fields (N = 1)
Total #MU/plan			
Plans Eclipse			
Mean	667.8 ± 164.3 (N = 11)	1548.0 ± 49.5 (N = 2)	–
Range	478.3–961	1513–1583	–
Plans Monaco/ XiO			
Mean	775.9 ± 73.4 (N = 4)*	1215 (N = 1)	843.6 (N = 1)
Range	683.8–863.2	–	–
Total #CP/Field/Arc			
Plans Eclipse			
Mean	178 (N = 11)	187.1 ± 21.2 (N = 2)	–
Range	–	172.1–202.1	–
Plans Monaco/ XiO			
Mean	105 ± 28 (N = 4)	53.2 (N = 1)**	35.4 (N = 1)***
Range	69–136	–	–

* Elekta VMAT plans had only 1 field that encompassed 2 arcs (3 institutions) or 4 arcs (1 institution).
** Plan created in Monaco to be delivered by a Varian linac.
*** 2 CPs per segment.

ends, TPS commissioning of small fields and MLC positioning uncertainties [21]. Anyway, a very good consistency of data was observed among institutions having the same technology (linac/MLC/TPS).

Another important factor to take in consideration in IMRT is the MLC leaf positioning accuracy as even small deviations can lead to significant dose differences [37,38]. Results of the Picket Fence test showed that the maximum and the median leaf bias were well within the established tolerances of ± 1 mm and ± 0.5 mm, respectively.

CT to density conversion of either relative electron or mass density is essential to calculate dose in inhomogeneous media being also verified during the on-site visit. A general failure was observed in trabecular and cortical bone reference materials, when considering a tolerance of 20 HU. However, this tolerance is probably too strict. Kilby et al. [39] in 2002 and Nakao et al. [40] more recently, in 2017, established relative electron density acceptance levels for different tissue

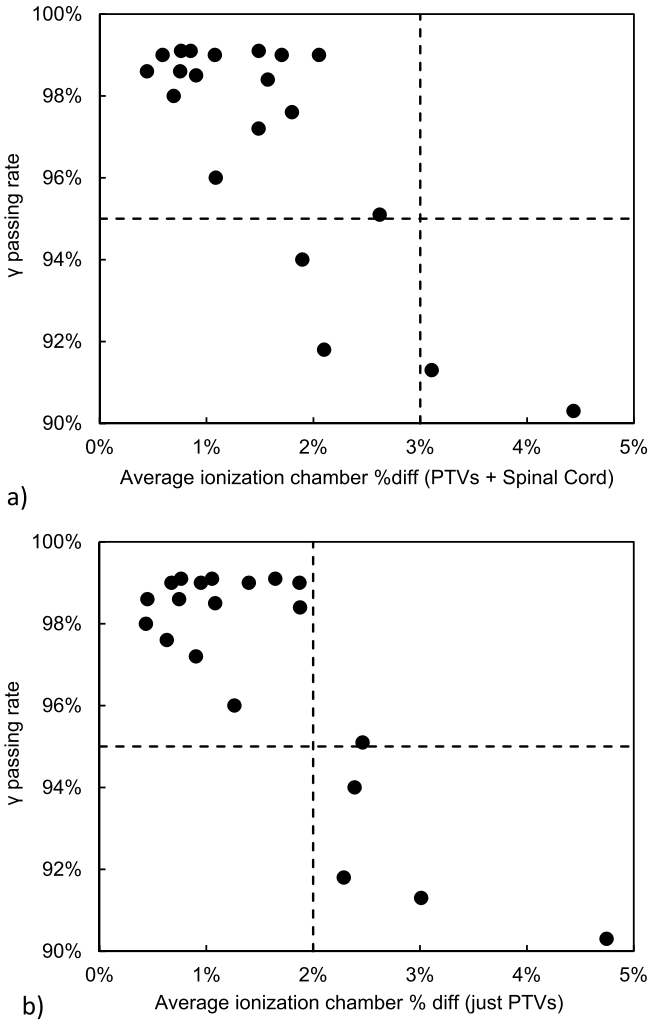

Fig. 3. Correlation between film gamma passing rates and average absolute ionization chamber deviations: a) including all four IC measuring points; b) excluding spinal cord measurement point.

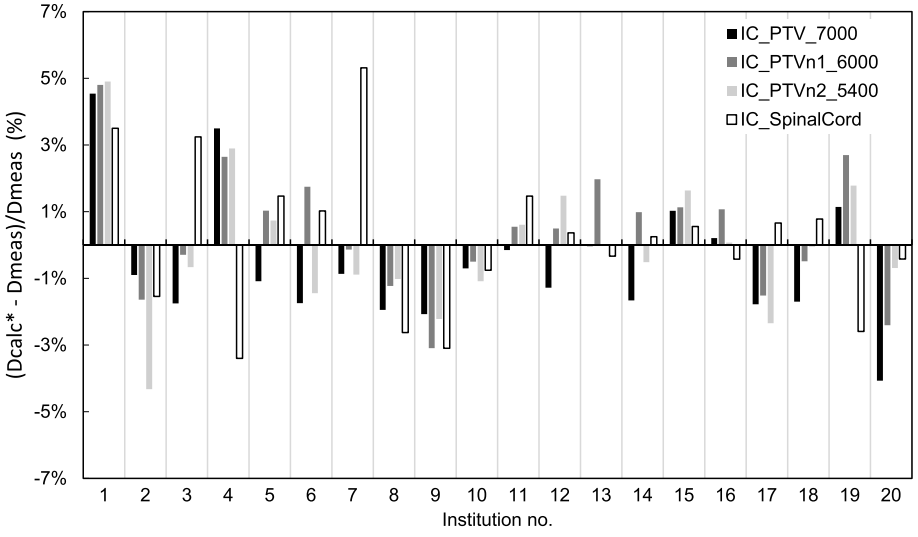

Fig. 2. Percent dose difference between calculated dose corrected for daily output variation – D_{calc*} – and measured dose in PTVs and spinal cord.

types. Nakoa et al. proposed a tolerance of ± 0.053 in RED difference for 6 MV and ± 0.044 for 6FFF MV for bone. These would correspond to around ± 100 HU and ± 80 HU, for 6 MV and 6FFF MV, respectively. If adopting these tolerances, the percent of failures would decrease to 5% in trabecular bone and 53% in cortical bone. The persisting differences may be due to the use of different calibration phantoms, tissue substitute materials and lack of points in the high density region of the conversion curves. A recommendation on the revision of the materials utilized in that region was given.

Regarding reference dosimetry and the corresponding daily output checks, a very good agreement was obtained with the percent difference between TPS calculated and measured doses of $-0.6\% \pm 0.9\%$ (1SD), averaged among institutions. Nevertheless, some issues have been noticed that may have contributed for some of the higher deviations. One example is the dose calculation in reference conditions for Monte Carlo based TPSs, which requires a careful assessment namely concerning the adopted calculation dose uncertainty and the grid size.

The dosimetric verification of the created H&N IMRT plan using both ionization chamber and EBT3 film showed that all the audit plans were within the established tolerances. Only four institutions had passing rates below 95% and IC differences above 2% in PTVs – Fig. 3b). The greater uncertainty in the IMRT dose delivery for these four institutions may be explained by some identified factors that include:

- Suboptimal plan dose distribution: reference measurement point(s) surrounded by a high dose gradient;
- Treatment plan complexity: much higher number of MUs or lower number of control points than other institutions using the same treatment technique;
- Inclusion of the treatment couch: 3 of these institutions did not account for the couch in treatment planning;
- Phantom positioning verification: alignment according to the lasers only or based just on planar MV imaging;
- Equipment age: audited linac was more than 10 years old in 3 of the 4 institutions; 2 institutions had a quite old TPS version which made it impossible to export the dose distribution in the coronal SHANE phantom corresponding to film with a resolution of about 1 mm, which could have affected the gamma analysis results [41];
- Small beam dosimetry modelling in the TPS: in 2/4 institutions, output factors for $3 \times 3\,cm^2$ and $2 \times 2\,cm^2$ field sizes were out of tolerance;
- Other factors may include experience of working with a newly installed TPS and consideration of all treatment plan parameters and its influence on dose calculation; heavy workload which made it difficult to dedicate enough time to perform the pre-visit activities on time and inherent audit preparation.

These four institutions used different IMRT techniques (SW, SS, and VMAT) and TPSs (Monaco, XiO, Eclipse). Generally no differences between groups of TPSs were identified in terms of deliverability, contrary to what has been reported by Clark et al. [17]. Clark et al., in a multi-institutional audit of rotational IMRT in the UK have shown that the gamma pass rates obtained for measurements performed using the audit system varied between TPS types. Plans created using TPSs designed for the manufacturer's own treatment delivery system (Eclipse and VoLO) gave significantly higher passing rates than the ones designed to be independent of the vendor (Monaco, OMP, and Pinnacle). It must be stressed that the pre-treatment QA verification had not predicted these sub-optimal results in any of these four institutions. Indeed, as other authors have reported, patient-specific QA results were poorly correlated with audit measurements [15,42], failing at identifying institutions that would not meet the acceptability criteria.

The audit plans had associated different levels of complexity as suggested by the total plan MU and the number of control points. VMAT plans created in Eclipse had a constant number of control points, 178, while it was variable in VMAT plans created in Monaco, being here a user definable parameter. Overall, no differences in terms of deliverability (audit results) were identified between these two groups of plans. Regarding the three sliding window plans, they have been calculated in different TPSs but all to be delivered by a Varian linac. The Monaco SW plan had much less control points per field (53.2) than the Eclipse SW plans (172.1 and 202.1) and this plan performed poorly than the Eclipse SW plans, belonging to the group of institutions with suboptimal results. The complexity of the created IMRT/VMAT plans and the correlation with the audit results will be further investigated in a future work.

For film analysis, the methodology proposed by the IAEA was strictly followed to enable comparisons among participating institutions from different countries. The influence of choosing different film dosimetry protocols and following different methodologies on the audit results, namely gamma passing rates, was not highlighted in this paper nor reported as an audit result as it was addressed in a previous work [43].

Portugal was one of the first countries that have implemented this IMRT/VMAT audit at the national level and the results occurred to be more consistent than those of the IAEA multicentre pilot study [26] based on which 5% dose agreement and 90% gamma pass rate criteria were established. The national audit results in Portugal suggest that tighter tolerances could be adopted such as 3% dose difference for ionization chamber measurements and 95% gamma passing rate for film analysis as 80% (16/20) institutions were able to meet these tighter criteria. To-date there have been 20 countries in Europe that requested a SHANE phantom from the IAEA for 2018–2021 together with the assistance of international experts that facilitate the audit by the national auditing organization. Once more results from different countries become available, the IAEA established pass/fail criteria based on the multicentre pilot may be re-examined.

5. Conclusions

The IAEA supported national audit methodology for IMRT dose delivery verification has been carried out in Portugal in 2018 and covered 100% of radiotherapy institutions performing IMRT treatments.

Analysis of tests to check basic small field dosimetry data and MLC performance showed a good compliance with the established tolerances. Verification of the created H&N IMRT plans revealed a general good agreement between calculated and measured dose distributions. Overall, the audit results showed that the status of TPS calculations and delivery for H&N IMRT in Portugal are within the specified tolerances. At the same time the audit identified factors that contributed to increased uncertainties in the IMRT dose delivery in some institutions, and the relevant recommendations for quality improvement were made.

This initiative was certainly important to increase the confidence of all involved professionals and to strengthen the cooperation among the Portuguese medical physics community, giving place for future scientific projects.

Funding

Part of this work was supported by FCT, the Portuguese Foundation for Science and Technology, through a PhD scholarship, reference SFRH/BD/118929/2016.

Declaration of Competing Interest

The authors declare that they have no known competing financial

interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors would like to thank staff from all audit participating institutions; Pavel Kazantsev, Paulina Wesolowska, Miguel Capela, Tiago Ventura and Josefina Mateus for their expert advice; the IAEA for lending the phantom; IPOCFG, E.P.E, for acting as pilot centre; Medical Physics Division of the Portuguese Physics Society for supporting the project.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ejmp.2019.08.013.

References

[1] Nutting CM, Morden JP, Harrington KJ, Urbano TG, Bhide SA, Clark C, et al. Parotid-sparing intensity modulated versus conventional radiotherapy in head and neck cancer (PARSPORT): a phase 3 multicentre randomised controlled trial. Lancet Oncol 2011;12:127–36. https://doi.org/10.1016/S1470-2045(10)70290-4.

[2] Izewska J, Lechner W, Wesolowska P. Global availability of dosimetry audits in radiotherapy: The IAEA dosimetry audit networks database. Phys Imaging Radiat Oncol 2018;5:1–4. https://doi.org/10.1016/j.phro.2017.12.002.

[3] Ibbott GS, Thwaites DI. Audits for advanced treatment dosimetry. J Phys Conf Ser 2015;573:12002. https://doi.org/10.1088/1742-6596/573/1/012002.

[4] Clark CH, Jornet N, Muren LP. The role of dosimetry audit in achieving high quality radiotherapy. Phys Imaging Radiat Oncol 2018;5:85–7. https://doi.org/10.1016/j.phro.2018.03.009.

[5] Clark CH, Aird EGA, Bolton S, Miles EA, Nisbet A, Snaith JAD, et al. Radiotherapy dosimetry audit: three decades of improving standards and accuracy in UK clinical practice and trials. Br J Radiol 2015;88:20150251. https://doi.org/10.1259/bjr.20150251.

[6] Weber DC, Vallet V, Molineu A, Melidis C, Teglas V, Naudy S, et al. IMRT credentialing for prospective trials using institutional virtual phantoms: results of a joint European Organization for the Research and Treatment of Cancer and Radiological Physics Center project. Radiat Oncol 2014;9:123. https://doi.org/10.1186/1748-717X-9-123.

[7] Miri N, Lehmann J, Legge K, Zwan BJ, Vial P, Greer PB. Remote dosimetric auditing for intensity modulated radiotherapy: a pilot study. Phys Imaging Radiat Oncol 2017;4:26–31. https://doi.org/10.1016/j.phro.2017.11.004.

[8] Nakamura M, Minemura T, Ishikura S, Nishio T, Narita Y, Nishimura Y. An on-site audit system for dosimetry credentialing of intensity-modulated radiotherapy in Japanese Clinical Oncology Group (JCOG) clinical trials. Phys Med 2016;32:987–91. https://doi.org/10.1016/j.ejmp.2016.07.002.

[9] Izewska J, Andreo P. The IAEA/WHO TLD postal programme for radiotherapy hospitals. Radiother Oncol 2000;54:65–72. https://doi.org/10.1016/S0167-8140(99)00164-4.

[10] Gershkevitsh E, Schmidt R, Velez G, Miller D, Korf E, Yip F, et al. Dosimetric verification of radiotherapy treatment planning systems: results of IAEA pilot study. Radiother Oncol 2008;89:338–46. https://doi.org/10.1016/j.radonc.2008.07.007.

[11] Gershkevitsh E, Pesznyak C, Petrovic B, Grezdo J, Chelminski K, Lopes MC, et al. Dosimetric inter-institutional comparison in European radiotherapy centres: results of IAEA supported treatment planning system audit. Acta Oncol 2014;53:628–36. https://doi.org/10.3109/0284186X.2013.840742.

[12] Lopes MC, Cavaco A, Jacob K, Madureira L, Germano S, Faustino S, et al. Treatment planning systems dosimetry auditing project in Portugal. Phys Medica 2014;30:96–103. https://doi.org/10.1016/j.ejmp.2013.03.008.

[13] Lafond C, Chiavassa S, Bertaut C, Boussion N, Chapel N, Chapron L, et al. DEMAT: a multi-institutional dosimetry audit of rotational and static intensity-modulated radiotherapy. Phys Medica 2019;32:664–70. https://doi.org/10.1016/j.ejmp.2016.04.008.

[14] Seravalli E, Houweling AC, Van Battum L, Raaben TA, Kuik M, de Pooter JA, et al. Auditing local methods for quality assurance in radiotherapy using the same set of predefined treatment plans. Phys Imaging Radiat Oncol 2018;5:19–25. https://doi.org/10.1016/j.phro.2018.01.002.

[15] Jurado-Bruggeman D, Hernández V, Sáez J, Navarro D, Pino F, Martínez T, et al. Multi-centre audit of VMAT planning and pre-treatment verification. Radiother Oncol 2017;124:302–10. https://doi.org/10.1016/j.radonc.2017.05.019.

[16] Clark CH, Hansen VN, Chantler H, Edwards C, James HV, Webster G, et al. Dosimetry audit for a multi-centre IMRT head and neck trial. Radiother Oncol 2009;93:102–8. https://doi.org/10.1016/j.radonc.2009.04.025.

[17] Clark CH, Hussein M, Tsang Y, Thomas R, Wilkinson D, Bass G, et al. A multi-institutional dosimetry audit of rotational intensity-modulated radiotherapy. Radiother Oncol 2014;113:272–8. https://doi.org/10.1016/j.radonc.2014.11.015.

[18] Veres A, Hallet JX. Equal-Estro experience in dosimetry audits in advanced techniques of radiotherapy – the tomotherapy example. SSDL Newsletter 2019;70:29–31 https://www-pub.iaea.org/MTCD/Publications/PDF/Newsletters/ssdl-70.pdf [accessed 26.06.2019].

[19] Molineu A, Hernandez N, Nguyen T, Ibbott G, Followill D. Credentialing results from IMRT irradiations of an anthropomorphic head and neck phantom. Med Phys 2013;40. https://doi.org/10.1118/1.4773309.

[20] Lechner W, Wesolowska P, Azangwe G, Arib M, Gabriel V, Alves L, et al. A multinational audit of small field output factors calculated by treatment planning systems used in radiotherapy. Phys Imaging Radiat Oncol 2018;5:58–63. https://doi.org/10.1016/j.phro.2018.02.005.

[21] Izewska J, Wesolowska P, Azangwe G, Followill DS, Thwaites DI, Arib M, et al. Testing the methodology for dosimetry audit of heterogeneity corrections and small MLC-shaped fields: results of IAEA multi-center studies. Acta Oncol 2016;55:909–16. https://doi.org/10.3109/0284186X.2016.1139180.

[22] Carson ME, Molineu A, Taylor PA, Followill DS, Stingo FC, Kry SF. Examining credentialing criteria and poor performance indicators for IROC Houston's anthropomorphic head and neck phantom. Med Phys 2016;43:6491. https://doi.org/10.1118/1.4967344.

[23] Izewska J. Development of quality audits for advanced technology in radiotherapy dose delivery. SSDL Newsletter 2016;64:8–15 https://www.iaea.org/publications/11032/ssdl-newsletter-issue-no-64-february-2016 [accessed 26.06.2019].

[24] International Atomic Energy Agency (IAEA). WORKING MATERIAL IAEA Supported National "End-to-End" Audit Programme for Dose Delivery Using Intensity Modulated Radiation Therapy through On-Site Visits to Radiation Therapy Institutions; 2019. https://dosimetry-audit-networks.iaea.org/Content/end-to-end%20CIRS%20SHANE/National%20end-to-end%20IMRT-VMAT%20audit%20methodology.pdf [accessed 13.06.2019].

[25] CIRS. Phantom Patient for VMAT & IMRT. http://www.cirsinc.com/products/all/119/shane-phantom-patient-for-vmat-and-imrt/ [accessed 26.06.2019].

[26] Kazantsev P, Clark C, Venencia D, Georg D, Gershkevitsh E, Van Dyk J, et al. New IAEA end-to-end on-site IMRT audit methodology: pilot test results. Proceedings of the International Conference on Advance in Radiation Oncology (ICARO2). Vienna: International Atomic Energy Agency; 2017.

[27] Followill DS, Kry SF, Qin L, Leif J, Molineu A, Alvarez P, et al. The radiological physics center's standard dataset for small field size output factors. J Appl Clin Med Phys 2012;13:282–9. https://doi.org/10.1120/jacmp.v13i5.3962.

[28] Followill DS, Kry SF, Qin L, Leif J, Molineu A, Alvarez P, et al. Erratum: "The Radiological Physics Center's standard dataset for small field size output factors". J Appl Clin Med Phys 2014;15:356–7. https://doi.org/10.1120/jacmp.v15i2.4757.

[29] International Atomic Energy Agency (IAEA). IAEA TRS-483: Dosimetry of small static fields used in external beam radiotherapy: an international code of practice for reference and relative dose determination. Vienna: International Atomic Energy Agency; 2017.

[30] International Atomic Energy Agency (IAEA). IAEA TRS- 430: Commissioning and Quality Assurance of Computerized Planning Systems for Radiation Treatment of Cancer. Vienna: International Atomic Energy Agency; 2005.

[31] Kazantsev P, Hernandez V, Luketin L, Izewska J. EP-2194: analysis of treatment planning feasibility of the multinational end-to-end IMRT audit methodology. Radiother Oncol 2018;127:S1212–3. https://doi.org/10.1016/S0167-8140(18)32503-9.

[32] International Atomic Energy Agency (IAEA). Absorbed dose determination in external beam radiotherapy: an international code of practice for dosimetry based on standards of absorbed dose to water. IAEA TRS-398. Vienna: International Atomic Energy Agency; 2000.

[33] Lewis D, Micke A, Yu X, Chan MF. An efficient protocol for radiochromic film dosimetry combining calibration and measurement in a single scan. Med Phys 2012;39:6339–50. https://doi.org/10.1118/1.4754797.

[34] Klein EE, Hanley J, Bayouth J, Carolina N, Simon W, Dresser S, et al. Task Group 142 report: Quality assurance of medical accelerators a. Med Phys 2009;36:4197–212. https://doi.org/10.1118/1.3190392.

[35] Husby E, Svendsen ED, Andersen HK, Martinsen ACT. 100 days with scans of the same Catphan phantom on the same CT scanner. J Appl Clin Med Phys 2017;18:224–31. https://doi.org/10.1002/acm2.12186.

[36] ICRU Report 91: prescribing, recording, and reporting of stereotactic treatments with small photon beams. J ICRU, 2014;14:31–53.

[37] Chang CC, Lin JC, Cheng HW, Tsai JT. Dose impact of systemic MLC position error for esophagus cancer plan: volumetric modulated arc therapy versus step and shoot modulated therapy. Int J Radiat Oncol Biol Phys 2015;93:E563. https://doi.org/10.1016/j.ijrobp.2015.07.1989.

[38] Mu G, Ludlum E, Xia P. Impact of MLC leaf position errors on simple and complex IMRT plans for head and neck cancer. Phys Med Biol 2008;53:77–88. https://doi.org/10.1088/0031-9155/53/1/005.

[39] Kilby W, Sage J, Rabett V. Tolerance levels for quality assurance of electron density values generated from CT in radiotherapy. Phys Med Biol 2002;47:1485–92. https://doi.org/10.1088/0031-9155/47/9/304.

[40] Nakao M, Ozawa S, Yamada K, Yogo K, Hosono F, Hayata M, et al. Tolerance levels of CT number to electron density table for photon beam in radiotherapy treatment planning system. J Appl Clin Med Phys 2018;19:271–5. https://doi.org/10.1002/acm2.12226.

[41] Huang JY, Pulliam KB, McKenzie EM, Followill DSKS. Effects of spatial resolution and noise on gamma analysis for IMRT QA. J Appl Clin Med Phys 2014;15:4690. https://doi.org/10.1120/jacmp.v15i4.4690.

[42] Kry SF, Molineu A, Kerns J, Faught A, Huang JY, Pulliam K, et al. Institutional patient-specific intensity-modulated radiation therapy quality assurance does not predict unacceptable plan delivery as measured by IROC Houston's head and neck phantom. Int J Radiat Oncol Biol Phys 2015;90:1195–201. https://doi.org/10.1016/j.ijrobp.2014.08.334.

[43] Santos T, Ventura T, Capela M, Mateus J, Lopes MC. Influence of film dosimetry protocols on IMRT audit results. Proceedings of the international symposium on standards, applications and quality assurance in medical radiation dosimetry (IDOS2019). Vienna: International Atomic Energy Agency; 2019.