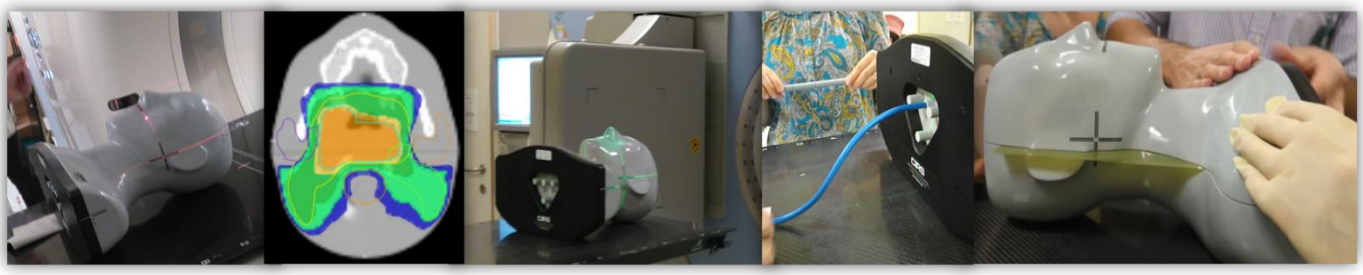
IAEA supported national IMRT audit in Portugal

National report



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Contents

1| Introduction

Intensity Modulated Radiation Therapy (IMRT) is becoming a commonly used treatment technique in many radiotherapy centres, although it is well known that it is very demanding in both planning and delivery process, leading to a higher probability of errors to occur.

To ensure the optimal and safe usage of the complex IMRT procedures, the IAEA has developed an IMRT audit programme to review physical aspects of IMRT treatments through on-site visits.

To be as close as possible to a patient treatment, the audit methodology simulates with a specially designed anthropomorphic head and neck (H&N) phantom – *the CIRS Shoulder Head and Neck End-to-End* (SHANE) – and a set of contours representing target volumes and organs-at-risk (OARs), all steps of an IMRT treatment, in an 'end-to-end' approach. A multicentre pilot study was conducted to test the audit methodology [1].

The IMRT audit has been carried out in Portugal with the IAEA assistance being IPOCFG the audit pilot centre, like it happened for 3D-CRT TPS audit in 2011/2012 [2]. The project is part of the PhD of Tania Santos who was nominated the national auditor, being her thesis supervisor at IPOCFG, Maria do Carmo Lopes, the national coordinator of the project. The Medical Physics Division of the Portuguese Physics Society (DFM_SPF) has given institutional support to this national project and included it in the Annual Plan for 2018. In August 2017 a letter was sent to all radiotherapy centres in Portugal in order to establish the list of participants on a voluntary basis. Then the national auditor and coordinator have joined the IAEA RER6033 Regional Workshop on QUATRO-Physics from 8 to 12 November 2017 in Seibersdorf/Vienna to get familiar with the audit methodology and discuss its implementation in Portugal.

The project phases included:

i. **Pre-visit activities**: the participating institutions were asked to perform some activities prior to the on-site visit that included: preparation of a preliminary treatment plan based on a reference set of CT images of the phantom and a pre-defined set of structures sent in DICOM RT format; and some tests to evaluate the MLC performance and to check small field dosimetry – December 2017 to February 2018.

ii. **Kick-off workshop:** a workshop was organized for medical physicists and dosimetrists from the involved radiotherapy centres to present the adopted methodology and discuss the audit implementation. This workshop was held on 10 March 2018. The project in Portugal was financially supported through the profits of this workshop – registration fees and technical exhibition with 9 participating companies. Eduard Gershkevitsh, an IAEA expert, participated as invited speaker. The scientific programme is presented in Appendix A of this report. The audit measurements at the pilot centre had been performed on the previous day, with the presence of the IAEA expert.

iii. **On-site visits**: the national auditor travelled through 20 radiotherapy centres between March and September 2018, spending two days at each institution. The first day was dedicated to CT scanning of the phantom, CT to RED or mass density review and treatment planning. The second day was reserved to perform the audit measurements. The national coordinator has been always available through remote phone contact during the visits.

iv. **Post-visit analysis**: analysis of all audit measurements and report of the audit results was carried out from September to November 2018 by the auditing team.

v. **Evaluation workshop:** to be held on 9 March 2019. The national as well as the European results will be presented and discussed. It will count with the participation of two IAEA experts, Joanna Izewska, Head of the Dosimetry Laboratory and Eduard Gershkevitsh.

2| Materials and Methods

2.1| National characterization

Portugal is a country geographically located in the extreme southwest of Europe. The national territory is divided in 18 administrative districts including also the Autonomous Regions of Azores and Madeira, two archipelagos in the Atlantic Ocean. The current population is estimated at 10.3 million, being the demographic concentration higher in the western coast region. Actually Lisbon and Porto are the cities with the highest population density. In both archipelagos of Azores and Madeira there are about 0.5 million inhabitants [3].

Concerning radiotherapy healthcare, there are presently, by November 2018, 24 radiotherapy centres equipped with 55 treatment machines including 52 linear accelerators, one Tomotherapy, one Cyberknife and one Gamma Knife. 8 out of these 24 centres are public institutions, having 29 treatment units. From the existing 52, two linacs are currently not treating patients waiting for replacement.

20 out of 24 centres have already introduced IMRT in clinical practice. Overall, patients treated with IMRT represent about one third of the total treated patients per year with external beam radiotherapy in the country, meaning that 3D-CRT is still the most used treatment technique. However when looking at individual centres numbers, there are three institutions where this percentage is above 50%. From the IMRT treatments, H&N patients represent on average 20%, ranging from 2% to 79%, in 2017. Regarding years of experience on H&N IMRT there are 7 centres with up to 2 years of experience (one of them had just started in the first semester of 2018), 9 centres with more than five years, and as for the remaining 4 institutions it varies from 2 to 5 years.

All 20 radiotherapy centres performing IMRT treatments have voluntarily participated in the audit project. For logistical reasons only one combination of treatment machine, TPS, dose calculation algorithm and beam energy was involved in the audit in each centre. The treatment units included: 19 linacs (14 Varian, 5 Elekta) and one Tomotherapy unit – Figure 1.

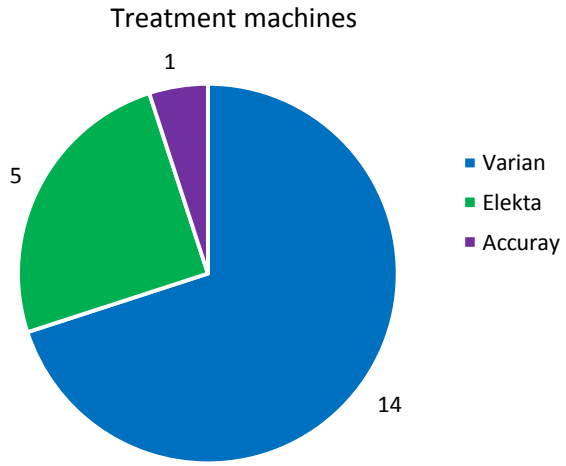

Figure 1 - Audited treatment machines – distributed by manufacturer.

The linac models included: Varian – Clinac (7), TrueBeam (5), Edge (1), Trilogy (1); Elekta – Synergy (4), VersaHD (1); Accuray – TomoHD (1). 70% (14/20) of these treatment machines are less than 10 years old and 10 of them have been installed in the past 5 years. The oldest unit, Clinac 6EX, was recently moved from one institution to another, and it has more than 15 years.

The units were equipped with different multileaf collimators, presented in Figure 2.

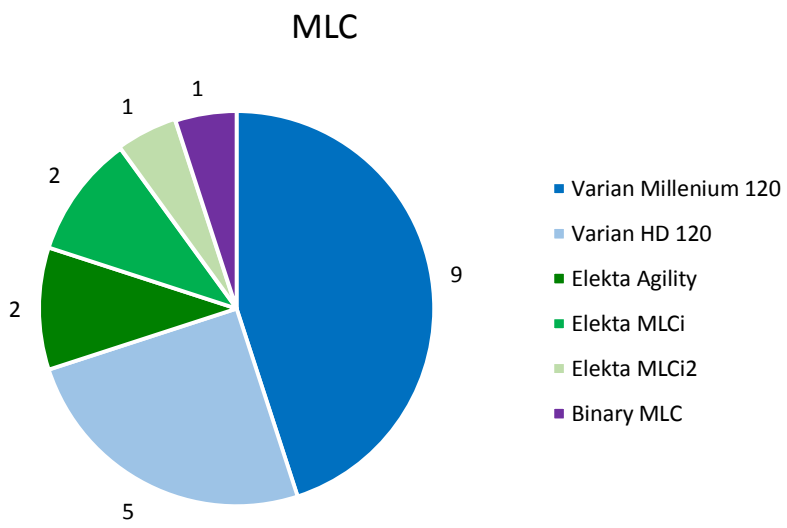

Figure 2 - Multileaf collimators.

Regarding beam energy, 18/20 centres used 6 MV and two 6FFF MV (Tomotherapy and one linac). The TPS grouped by commercial names included: 13 Eclipse (Varian), 5 Monaco (Elekta), 1 XiO (Elekta) and 1 VoLo (Accuray). The dose calculation algorithms involved in this audit are shown in Figure 3.

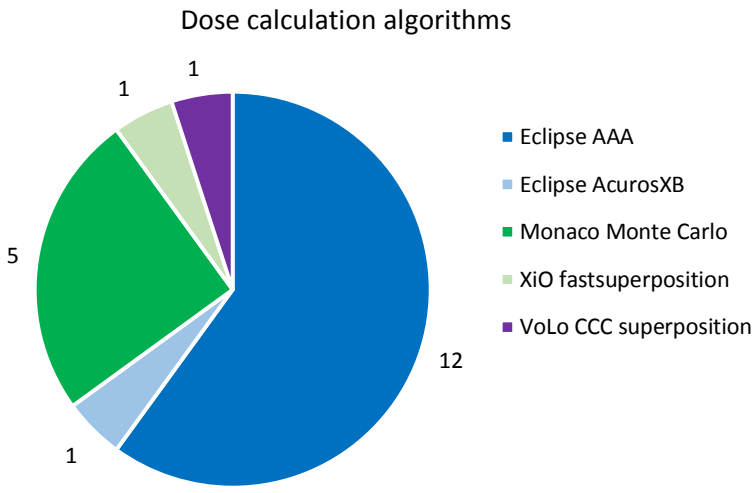

Figure 3 - Distribution of TPS dose calculation algorithms.

Fifteen out of 20 centres reported dose to medium and 5 dose to water. Dose calculation grid resolution varied between 1 and 3 mm: 1 mm (1), 2 mm (5), 2.5 mm (11) and 3 mm (3). The delivery IMRT techniques included: VMAT (15), Sliding Window (3), Step & Shoot (1) and Helical IMRT (1). 11/20 centres did not account for couch top in treatment planning.

There were two centres in which the audited equipment was not yet being used in clinical practice, though at a final commissioning stage. Both institutions perform IMRT treatments in other existing machines but wanted to be audited for the new machine which will be used for IMRT treatments as a final step of commissioning.

Overall the audited equipment sets including IMRT treatment techniques are shown in Table 1.

Table 1 - Audited radiotherapy equipment sets and techniques.

Linac	TPS	Algorithm	Technique	Nr of Centres
Varian	Eclipse	AAA	Sliding Window	2
			VMAT	10
		AcurosXB	VMAT	1
	Monaco	Monte Carlo	Sliding Window	1
Elekta	Monaco	Monte Carlo	VMAT	4
	XiO	Fast Superposition	Step & Shoot	1
Tomotherapy	VoLo	CCC Superposition	Helical IMRT	1

2.2| SHANE Phantom

The *CIRS Shoulder, Head and Neck End-to-End Verification Phantom* (CIRS Inc, Norfolk, VA, USA) mimics a typical H&N patient, including bone, soft tissue, teeth and air cavities – Figure 4. The phantom has four horizontal channels (superior-inferior) customized to insert a PTW TM31010 Semiflex 0.125 cc ionization chamber. A film can also be placed in a coronal plane to evaluate 2D dose distributions. Phantom has in the shoulders region seven calibrated electron/mass density reference plugs – lung inhale, lung exhale, water vial, soft tissue, spinal cord, trabecular bone and cortical bone – allowing to verify the conversion of HUs to relative electron/mass density.

Figure 4 - SHANE phantom [4].

2.3| Audit phases

2.3.1| Pre-visit activities

The participating institutions were asked to perform several preliminary activities before the audit took place. The methodology, DICOM files and an Excel report form with instructions on how to perform each requested test were sent several months before the on-site visit.

The pre-visit activities can basically be divided into two groups: ***I.*** small beam dosimetry verification and MLC performance test and ***II.*** pre-visit planning exercise. The tests included in group ***I*** were: 1) calculation on TPS of 5 MLC shaped field (6 x 6 cm^2, 4 x 4 cm^2, 3 x 3 cm^2 and 2 x 2 cm^2) output factors (OF) taking the 10 x 10 cm^2 as the reference. The calculated OF were then compared to the Imaging and Radiation Oncology Core, IROC – Houston QA Centre reference dataset [5,6]. Tolerances of ±3% for the 2 x 2 cm^2 field and ±2% for larger fields (3 x 3 cm^2, 4 x 4 cm^2 and 6 x 6 cm^2) were considered. 2) Calculation on TPS of in-plane and cross-plane profiles for a MLC-shaped 2 x 2 cm^2 field. The differences between centres results and IAEA baseline data for field size and penumbra widths (20%-80%) were determined. The considered tolerances were: ±2 mm for field size and ±3 mm for penumbras. In Synergy linacs equipped with MLCi or MLCi2, with X backup jaws, to measure

leaves transmission, X backup jaws should had been kept away from the MLC leaves, which was not possible to configure in one centre. 3) Performance of picket fence/band test using the local procedure (film/EPID). Resulting files (EPID image in DICOM format or scanned film) were sent to the auditing team for analysis. This group of activities was not performed at the pilot centre. Tomotherapy machine is equipped with a binary MLC, meaning that the leaves can only be open or closed, so the proposed MLC test cannot be performed. The standard references of basic dosimetry do not apply as the 10 x 10 cm^2 homogeneous field cannot be considered.

As for group ***II***, a CT images set – reference CT dataset (401 slices, with a thickness of 1 mm) – of the SHANE 3 phantom as well as the associated pre-delineated structures including three target volumes (PTV_7000, PTVn1_6000 and PTVn2_5400) and four organs-at-risk (spinal, brainstem, left parotid and right parotid) were provided by IAEA. The clinical test case simulates a patient with a nasopharynx tumour. Participants were requested to import the files in TPS and check the volume of each structure against the values given by IAEA. Then, they had to create a preliminary treatment plan with the usual local planning technique, dose calculation algorithm, grid resolution, correction for treatment couch, etc., as if it were a typical H&N patient. A list of dose-volume objectives and constraints was provided to guide the planning process. ICRU 83 recommendation of reporting D_{50} as the prescription dose should had been followed [7]. Once having the plan ready, the dose-volume-histograms of each structure were reviewed and the doses achieved recorded and compared with the provided prescription aims. Patient-specific QA of the created plan was done following the local procedure to verify its deliverability. After that, all data was sent to the auditing team for review and analysis.

2.3.2| On-site visits

The audit was first performed at the pilot centre in the presence of the IAEA expert. Before the irradiations, the local dosimetry system composed of a TM31010 Semiflex 0.125 cc ionization chamber and UNIDOS E electrometer (PTW-Freiburg) was intercompared with the one from IAEA, to ensure the metrological quality of its calibration. The result was within 0.2%. This dosimetric system has been travelling around the participating centres and tested for constancy against a Sr-90 source after each travel.

The on-site visits were conducted by the national auditor between March and September 2018. One centre was visited in March, two in April, five in May, five in June, five in July and one in September. The auditor took with her the following equipment: CIRS SHANE phantom and accessories, calibrated Semiflex 0.125 cc ionization chamber, UNIDOS E electrometer, dosimetric cable, barometer, thermometer, slab of solid water (Gammex, Sun Nuclear Corporation, Melbourne USA) drilled to insert the Semiflex (30 cm x 30 cm x 2 cm), box with Gafchromic EBT3 films (appropriately cut, numbered and marked), gloves, personal dosimeter and IMRT audit reporting form.

a) CT scan and CT to RED/mass density conversion verification

The on-site visit started by performing a CT scanning of the SHANE phantom (including the shoulders region that contains the different density plugs) – clinical CT set – following the local CT scanning protocol for H&N patients. For scanning, the ionization chamber channels were filled with solid rods that included radiopaque markers.

Out of the 20 CT scanners that entered the audit, 55% were from Siemens, 30% from GE and 15% from Philips. Regarding the local scanning H&N protocol, 13 centres used a kV setting of 120 kV, six used 130 kV and one 110 kV. Slice thicknesses varied from 2 to 3 mm, with eight centres using 2 mm, six using 2.5 mm and six using 3 mm.

On the CT software a ROI of about 1 cm diameter was delineated in two slices within the different density plugs: lung inhale, lung exhale, water, trabecular bone and cortical bone in addition to air, soft tissue and spinal cord regions. Having the measured HU and reference RED/mass density provided by CIRS, the reference CT to RED/mass density calibration curve was obtained. After importing the acquired CT in TPS, the same exercise was repeated. A ROI of about 1 cm was delineated in the same slices of the mentioned different density regions.

The displayed HU and the corresponding RED/mass density were recorded. Then, the TPS CT to RED/mass density was compared with the calibration one. Differences of ±20 HU were considered acceptable for all materials except water, for which the tolerance was of ±5 HU.

b) Treatment planning phase

The PTV and OAR structures were transferred from the reference CT (sent before the on-site visit) to the clinical planning CT through co-registration of the two sets of images. After that, the volume of each defined contour was verified. The provided set of contours included four structures that represented the ionization chamber volume, “IC_PTV_7000”, “IC_PTVn1_6000”, “IC_PTVn2_5400” and “IC_SpinalCord” surrogating the measurement reference points.

The pre-visit plan was then transferred (copied or saved as template) to the clinical CT set and re-optimized. Dose-volume data for all target volumes and organs-at-risk were recorded in the IMRT audit reporting form, as well as the mean plan dose at the virtual ionization chamber volumes. Homogeneity of dose distribution in those volumes was also evaluated through the calculation of a homogeneity index, HI [(Dmax-Dmin)/Dmean]. Dose distribution at the coronal plane corresponding to film position was saved in DICOM RT format, with a resolution of about 1 mm x 1 mm, when possible.

c) Beam ouput check and MLC tests (preparation)

At the pilot centre, a plan was created on TPS to deliver 2.5 Gy to a small volume in the centre of the Cheese phantom (cylindrical phantom that can only accommodate the Exradin A1SL ion chamber or equivalent in diameter), considering SAD = 85 cm and field width of 2.5 cm. The local dosimetry system composed by an Exradin A1SL ion chamber (SDD = 85.5 cm) and TomoElectrometer both from Standard Imaging (Wisconsin USA) was used to verify the daily rotational variation and its consistency with TPS. Then, the local and auditor’s dosimetry systems were compared. For that, a machine procedure was created to perform an irradiation considering: the machine specific reference field of 5 x 10 cm^2 [8], treatment time of 30 seconds, SSD = 85 cm and depth 10 cm. The difference between both dosimetry systems was less than 0.5%.

The on-site visits included, in each centre: beam output verification with the auditor’s dosimetry system referred above, irradiation of an EBT3 film with a 2 x 2 cm^2 MLC shaped field, performance of Picket Fence/Band test and irradiation of reference strips for film calibration.

To confirm the reference dose machine calibration as calculated in TPS, a reference plan was created for a slab solid water phantom. Not all centres had measured the correction factor solid water-water neither had a CT scan of a solid water phantom. Therefore, in 17/19 institutions, a CT scan of a slab phantom built as shown in Figure 5 was done. The ionization chamber channel was filled with a solid plug for scanning.

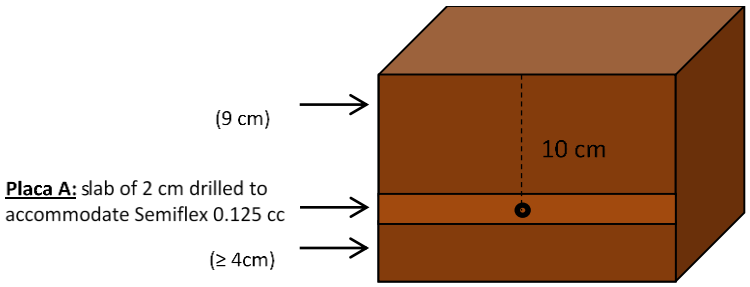

Figure 5 - Solid water phantom #1.

All visited centres had either a 30 x 30 cm^2 IBA RW3 or PTW RW3 slab phantom. MUs to deliver 2 Gy in reference conditions, field size of 10 x 10 cm^2 at SAD = 100 cm and 10 cm depth were calculated on TPS.

A second CT scan was done to a solid water phantom built without the customized “Placa A”. On that CT set, MUs to deliver 6 Gy for a field size of 2 x 2 cm^2 – as defined in the pre-visit activities – at SAD = 100 cm

and 10 cm depth were calculated. In addition, MUs to irradiate the reference strips for film calibration were determined, considering the reference field of 10 x 10 cm^2, SAD = 100 cm and 10 cm depth.

Regarding MLC performance test, Elekta support created and provided to all users a test following the IAEA specifications (5 strips of all MLC length, 3 cm gap between strips and minimum achievable leaf openings), however, the delivery mode was set as static, even for those centres performing VMAT treatments. For Varian machines, the auditing team asked physicists from two institutions (with a linac equipped with Varian Millennium 120 MLC and a linac with Varian HD 120 MLC) who had created by themselves a pattern according to the IAEA instructions to provide the corresponding files. These files were sent to all Varian radiotherapy centres and the test locally created.

d) On-site measurements

The on-site measurements were performed on the second day.

Patient-specific verification of the created IMRT plan was done following the local procedures and equipment, as for a typical IMRT H&N patient. Some centres used more than one verification method. A summary of the utilized systems is presented in Table 2.

Table 2 – Local verification systems used to validate the H&N IMRT audit plan.

System	Manufacturer	# Centres
Image detector dosimetry	EPID dosimetry (Varian Medical Solutions, Palo Alto, USA); Dosimetry Check (LifeLine Software Inc., Austin, USA)	8
MatriXX	IBA Dosimetry, Schwarzenbruck, Germany	4*
ArcCHECK	SunNucelar Corportation, Melbourne, USA	4
Octavius II + PTW 729 array	PTW, Freiburg, Germany	1
Octavius 4D + PTW 1500 array + Ion chamber measurements	PTW, Freiburg, Germany	3
EBT3 film + Ion chamber measurement	Ashland ISP Inc., Wayne, USA	2
Ion chamber measurement		2**
Independent MU/dose calculation	RadCalc (LifeLine Software Inc., Austin, USA); Mobius3D (Varian Medical Systems, Palo Alto, USA)	3

* In one centre the MatriXX array was used in combination with a slab phantom and in three centres with MultiCube; in one of them it was also attached to the gantry head, and COMPASS software was employed to reconstruct 3D dose. ** Ion chamber measurement in combination with a slab solid water phantom.

MLC test

MLC test was performed on EPID or film. Film was used for all Elekta machines (5/5) and EPID for most of Varian machines (11/14). Film was positioned isocentrically on the solid slab phantom (SAD = 100 cm) with an added build-up of at least 2 cm. EPID was positioned as close as possible to the isocenter.

Beam output check

Daily output of the machine was checked against the reference dose calibration modelled in the TPS with the auditor's equipment. The slab solid water phantom as considered for calculation was aligned on the treatment couch and the calculated MUs in TPS to delivery 2 Gy for a 10 x 10 cm^2 field size, 10 cm depth and SAD = 100 cm were administrated. Measured dose was determined according to TRS 398 dosimetry protocol [9] and compared with calculated dose as follows:

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

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

Irradiation of an EBT3 film with a 2x2 cm^2 MLC shaped field

An EBT3 film of 5 x 15 cm^2 was placed at 10 cm depth on the central axis at 100 cm SAD and irradiated with the defined 2 x 2 cm^2 MLC shaped field. Isocenter position was marked on film through laser alignment.

Dosimetric verification of the SHANE H&N treatment plan

SHANE phantom was positioned on the treatment couch and aligned through lasers. Phantom positioning was verified according to the local standard H&N IGRT method. Most of the centres (17/20) used kV CBCT, 1/20 used MV portal imaging, 1/20 MVCT and finally 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 lack of RTT support. The phantom alignment was generally verified once, before starting the measurements, with the ionization chamber already placed in the channel corresponding to the measurement point in PTV_7000.

Dosimetric verification of the created treatment plan was done through ionization chamber measurements and EBT3 film irradiation. Starting with point dose measurements, ion chamber was positioned in one of the four channels ("IC_PTV_7000","IC_PTVn1_6000", "IC_PTVn2_5400" and "IC_SpinalCord"), and two or three irradiations were performed per reference point, depending on the readings reproducibility. If the difference between the first two measurements was less than 0.5%, generally only two were done. Absorbed dose was determined according to IAEA TRS 398 formalism [9]. The calculated and measured doses were compared using equation (1) but taking D_{cal} as the corrected calculated dose for daily output variation – D_{cal^*}. Tolerances of ±5% for PTVs and ±7% for spinal cord were considered. Once completed ionization chamber measurements, and before disassembling the phantom to place the EBT3 film, lasers position was marked in tape on the phantom surface so that the film would not need to be irradiated to verify its correct alignment. EBT3 film was given a dose corresponding to three treatment fractions as per IAEA methodology. After measurements with SHANE, the reference strips were irradiated with the calculated MUs for film calibration.

2.3.3| Post-visit analysis

The IMRT audit forms were revised by the national auditing team. All films resulting from MLC positioning test, small field irradiation and SHANE IMRT plan verification were analysed centrally by the auditing team at the pilot centre.

a) MLC test

Picket Fence tests performed on EPID were analysed using the freeware software *Pylinac*, implemented as a web app – *Assurance QA* (https://pylinac.readthedocs.io/en/stable/). The EPID image (in DICOM format) was uploaded, MLC selected and then the software determined the maximum leaf bias and absolute median error in module (there is no possibility to choose mean error in the web app version). Films were scanned at the pilot centre and analysed in FilmQA PRO software. A maximum leaf bias within ±1 mm and median within ±0.5 mm was considered acceptable. The same methods were used to analyse pre-visit MLC tests.

b) Film scanning and calibration procedures

Film measurements were done in all institutions with EBT3 films (Ashland ISP Inc., Wayne USA) from a single batch (LOT #10241701). They were always handled with gloves and kept in a black envelope when not being used to minimize exposure to light.

All films were scanned at least 48 h from irradiation by the national auditor at the pilot centre, using a flatbed scanner Epson Expression 10000 XL (Seiko Epson Corporation, Japan). To ensure stabilised scanner response, films were digitized after a warm-up time of at least 30 minutes and performance of 16 empty scans. Each film was placed at the same central location in landscape orientation with a glass compression plate on top. RGB images were acquired in transmission mode, at 48 bits colour depth and a spatial resolution of 72 dpi (0.35 mm/pixel), with all colour correction options disabled. Scan was repeated four times and resulting files were saved in .tiff format.

For the determination of the film dose response, 10 film strips (2.8 x 10 cm^2) were irradiated at the pilot centre, on a Siemens Oncor Avant Gard linear accelerator, in 6 MV photon mode. Strips were placed in a solid water phantom perpendicularly to the beam axis, at a depth of 10 cm, and exposed to known doses (0, 1, 2, 3, 4, 5, 6, 7, 8 and 9 Gy) in a 10 x 10 cm^2 field, SAD = 100 cm. Linac output fluctuation was taken into account. Calibration strips were scanned simultaneously in single mode scan, 48 h after irradiation. The scanned pixel

values as a function of dose were determined for each channel (red, green and blue) from the average pixel values in a central region of interest of 1 x 1 cm^2. A generic calibration function per colour channel was then obtained.

It is well known that EBT3 film response is energy independent [10]. Nevertheless when analysing a given application film from one institution, the generic fitting calibration function established at the pilot centre was linearly re-scaled by means of two reference strips irradiated at each centre, one non-irradiated and the other one irradiated at 10% over the maximum dose. The reference strips were simultaneously scanned with the application film. This method allows to fit the actual scanning conditions, mitigating scan-to-scan variability, and forces the calibration into agreement at the reference dose levels [11].

c) 2 x 2 cm^2 field film analysis

For the 2 x 2 cm^2 irradiated film, triple channel dosimetry was performed using a home-made software, Matlab R2010a, developed at IPOCFG, based on the work published by Lewis et al. [11], Ferreira et al. [12], and Mayer at al. [13]. The resulting RGB dose map was imported in RIT113 version 5.1 (Radiological Imaging Technology, Inc., Colorado Springs USA).

Marks on the film indicating the isocenter position were used as a guide to obtain the film measured cross-plane and in-plane profiles. The film dose was normalized to the profiles intersection value. Measured field size (defined as the normalized dose profile FWHM) and penumbra width (20-80%) were compared with the ones from TPS generated profiles. Differences up to ±2 mm and ±3 mm, respectively, were considered acceptable.

In Varian machines secondary jaws were set at a 10 x 10 cm^2 field size with the closed MLC leaves parked outside the field. In Elekta, y-jaws defined the field in-plane dimension. Therefore, to measure transmission in-plane profiles were considered at 4 cm from the field centre determining average transmission values, including both interleaf and intraleaf transmission.

d) SHANE films analysis

The agreement between the dose distribution in film and calculated by the TPS was evaluated with FilmQA Pro software using triple channel dosimetry. 2D relative global gamma analysis was performed within the ROI defined by film fiducials, with normalization done to a high dose low gradient region inside PTV_7000. The acceptance limit for global gamma analysis was 90% passing rate for a criterion of 3%/3mm with 20% dose threshold. TPS dose distribution was considered the reference, implying that the film dose distribution was rescaled to the resolution of the TPS dose grid.

2.3.4| Reporting

Once the analysis has been completed, the audit reporting forms were sent to the responsible medical physicist at each radiotherapy centre. The present report is provided to IAEA together with the complete set of sent results.

3| Results

3.1| Pre-visit activities

Two centres had not completed the pre-visit activities before the on-site visit took place, however the corresponding files were sent after that.

Small beam dosimetry verification and MLC performance test

Output factors (OF) were calculated in 19/20 institutions, but one of them used 6FFF MV beam energy and there was no reference data for that photon mode. Also for Tomotherapy the concept of OF as per the methodology does not apply. Therefore, OFs calculated on TPS by 18 institutions, using 6 MV as nominal beam energy, were gathered and analysed. The percent differences between calculated and IROC-Houston QA Centre's reference data were determined and are presented in Figure 6 as a function of field size. Each institution has been assigned a different colour. The tolerance limits of ±3% for the 2 x 2 cm^2 field and ±2% for larger fields (3 x 3 cm^2, 4 x 4 cm^2 and 6 x 6 cm^2) are represented by the red lines.

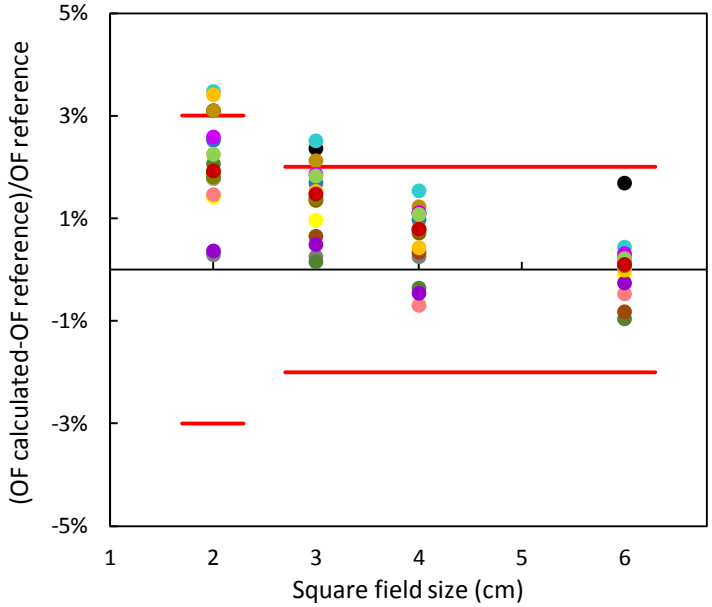

Figure 6 - Percent difference between OF calculated on TPS and the reference OF (N=18) as a function of square field size.

On average, the audited TPSs overestimated OFs in comparison to the reference IROC dataset which is in line with previous IAEA reported findings [14], but differences were generally within the tolerances. Three institutions had a deviation higher than 2% for 3 x 3 cm^2 field size and four exceeded the tolerance of 3% for the 2 x 2 cm^2 field.

In-plane and cross-plane profiles for the 2 x 2 cm^2 field were calculated and compared with the IAEA reference's dataset. Concerning cross-plane profiles, the differences between field sizes and penumbra widths were within ±2 mm and ±3 mm in all institutions, for both Elekta and Varian linacs. In-plane profiles generated in TPS (Monaco/XiO) for Elekta linacs (N=5) were also complying with these tolerances. When considering Varian linacs, all centres using Eclipse TPS (N=12) had the in-plane field size out of tolerance, however the reported values were very consistent among centres, 19.5 ± 0.1 mm (1SD), on average.

In the pre-visit phase, local medical physicists were requested to check the MLC performance as they usually do in clinical practice. Four of these tests could not be analysed by the auditing team given the local specificities. The results of the remaining MLC tests were within ±0.5 mm for the leaf positioning bias. Absolute maximum error was on average 0.18 ± 0.09 mm (1SD), maximum of 0.47 mm and the median leaf error was 0.04 ± 0.02 (1SD), maximum of 0.09 mm.

Pre-visit planning

Volume verification of the DICOM provided structures was done. The reported volumes by the different institutions were fairly consistent, regardless the used TPS. The preliminary H&N IMRT treatment plans have generally met the planning constraints. Minor violations included for example, not reporting D_{50} as the prescription dose (7/20). Pre-treatment QA results of the created plans indicated that all were deliverable according to the local analysis method and acceptance limits.

Results were sent to all centres.

3.2| On-site visits

CT to RED conversion

The majority of CT scanners that entered the audit were dedicated to radiotherapy. Most of the centres had used an appropriate phantom with tissue equivalent materials to obtain the initial CT to RED/mass density conversion curve but apparently some do not check its constancy as often as it is recommended [15].

The on-site verification with SHANE revealed a general failure in trabecular bone (74%) and cortical bone (95%) reference materials. The differences may be due to the use of different materials for CT calibration and lack of points in high density region corresponding to the cortical bone taken as reference. Moreover, some smaller differences, just above the ±20 HU tolerance, mostly registered in trabecular bone and also (in minor scale) in lung inhale may be due to the different shapes, sizes and compositions of the phantoms and also the lack of regular checking of measured HU. Besides the general failure on those two reference materials, other discrepancies were noticed and corrected during the on-site visit, being the H&N IMRT plan calculated using the updated CT to RED curve. For instance, missing materials were added. Air was absent in one curve, having the first point a RED of 0.19 which translated into a difference of about 212 HU in air; water was added in another centre as a discrepancy of 44 HU was observed. The greatest correction happened in two centres that had mixed CIRS Head & Torso (lung, adipose, water, muscle, bone substitutes) with CATPHAN materials (PMP, LDPE, polystyrene, acrylic, derlin, teflon) to get one CT to RED curve with more data points. The introduced curve on TPS had a shape as shown in Figure 8 – “Cal 2016 CIRS Head & Torso + CATPHAN” which had not been noticed by the local medical physics team. This translated into differences up to 239 and 394 HUs in trabecular and cortical bone reference materials, respectively – “Cal 2018 CIRS SHANE”. After removing the data points corresponding to CATPHAN materials, the CT to RED curve – “Cal 2016 CIRS Head & Torso” – was much like the one measured on-site with SHANE, as it can be seen in Figure 7.

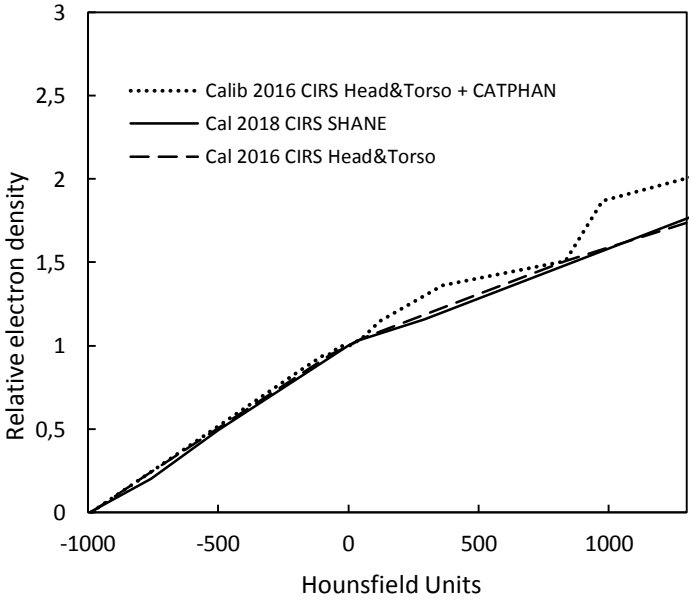

Figure 7 - Comparison between CT to RED conversion curves obtained with data from measurements carried out in 2016 and in the IMRT audit in one of the visited centres.

In summary, concerning the CT to RED conversion curves introduced on TPS, it is recommended a revision of the materials used in the high density regions, namely in those centres presenting huge differences in cortical bone. CT to RED calibration errors can compromise the dosimetry accuracy, depending on the treatment technique and beam energy used [16].

Treatment plans

The volume of all clinical contours transposed from the reference dataset to the locally acquired SHANE CT through co-registration was recorded. Despite corresponding to 20 different scans, the calculated volumes of the defined structures have shown a very good consistency among all centres as reported in Table 4.

Table 4 – Statistics of calculated structure volumes among all centres.

Structure name	mean	SD	min	max
		(cm^3)		
PTV_7000	87.9	0.5	87.0	88.5
PTVn1_6000	410.5	1.4	405.9	412.8
PTVn2_5400	258.5	1.3	254.6	260.4
SpinalCord	25.3	0.3	24.8	25.9
SpinalCord_03	57.9	0.4	57.3	58.8
BrainStem	43.5	0.3	43.1	44.0
BrainStem_03	70.9	0.5	69.6	71.8
Parotid_L	19.4	0.2	19.0	19.7
Parotid_R	22.4	0.3	22.1	22.8
IC_PTV_7000	0.10	0.05	0.01	0.20
IC_PTVn1_6000	0.11	0.05	0.06	0.21
IC_PTVn2_5400	0.11	0.04	0.06	0.17
IC_SpinalCord	0.13	0.05	0.07	0.23
Channel_1	46.2	0.7	44.2	47.1
Channel_2	46.2	0.7	44.3	47.1
Channel_3	46.3	0.7	44.5	47.3
Channel_4	46.2	0.7	44.5	47.3

Very often when Varian Eclipse was used for image registration, the volumes of “IC_PTV_7000” and “IC_PTVn1_6000” were below or just above the inferior tolerance limits. In most situations, when these structures resulted too small, to not modify them, an auxiliary structure was created using the BB markers as a guide just to evaluate the difference between them in terms of calculated mean dose.

The preliminary plan was used as a template or simply copied to the clinical SHANE CT set in the majority of the institutions aiming at speeding up the treatment planning phase. However re-optimization has been always needed. Generally it took several hours to get an acceptable plan. In the end, all treatment plans have met the proposed constraints except three where at least one of them was marginally not accomplished. Some irradiation technique related characteristics of the created H&N treatment plans, including the number of control points (CP) per field/arc are presented in Table 5.

Table 5 - Treatment plans characteristics.

	Delivery technique		
	VMAT (N=15)	**Sliding Window (N=3)**	**Step & Shoot (N=1)**
# Fields/Arcs	2 Arcs: 10; 3 Arcs: 2; 4 Arcs: 3	9 fields: 3	7 fields: 1
Total # MU/plan			
Plans Eclipse			
mean ± 1SD	667.8 ± 164.3 (N=11)	1548.0 ± 49.5 (N=2)	-
range	478.3 – 961	1513 – 1583	-
Plans Monaco/XiO			
mean ± 1SD	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 ± 1SD	178 (N=11)	187.1 ± 21.2 (N=2)	-
range	-	172.1 – 202.1	-
Plans Monaco/XiO			
mean ± 1SD	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 centres) or 4 arcs (1 centre); ** Plan created in Monaco to be delivered by a Varian linac; *** 2 CPs per segment

Most of the centres performing VMAT (10/15) created a treatment plan with 2 arcs. Two centres used 3 arcs and three created a plan with 4 arcs. All institutions performing sliding window used 9 beams.

Of notice is the great difference (about 2 times, on average) in total number of MU between sliding window and VMAT plans. And also the large spread of total MU for VMAT plans created on Eclipse. When comparing VMAT plans from Eclipse and Monaco, the number of CPs per arc was constant (178) and always higher in Eclipse, while variable in Elekta plans (ranging from 69 to 136), being a commonly user defined parameter.

A huge difference can be observed between the number of CPs 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).

For Tomotherapy plan (not included in Table 4) the treatment time was 302.1 s and the total number of CPs was 974, corresponding to 19.7 gantry rotations with a gantry period of 15.3 s, for a couch travel of 20 cm.

Pre-treatment verification of the created plans was performed using the local equipment and evaluation methods. Gamma analysis was the most widely used comparison method and 95% (3%/3mm) the acceptability criteria adopted in the majority of centres. All plans were considered deliverable by the local medical physicists.

MLC test

MLC tests from 18 institutions were analysed. This test was not performed in one centre due to an unexpected technical problem. Absolute maximum leaf bias was within the acceptance limit of ±1 mm for all institutions, being the overall average of 0.19 ± 0.11 mm (1SD), maximum of 0.49 mm. The median values were also within the adopted tolerance of ±0.5 mm, with average of 0.05 ± 0.03 mm (1SD), and maximum of 0.10 mm.

2 x 2 cm^2 field profiles

Measured in-plane and cross-plane profiles for the 2 x 2 cm^2 field were obtained and field size and penumbra widths compared with the ones calculated in TPS. Differences were within ±2 mm for both field size and penumbras in all institutions. A summary of the measured and calculated field size and penumbras is presented in Table 6. Overall, a very good consistence was observed for both measured and calculated data among centres equipped with the same technology (linac/MLC/TPS).

Table 6 - Summary of measured and calculated field sizes and penumbra widths – mean ± 1SD – for the 2 x 2 cm^2 field.

	Cross-plane profile			In-plane profile		
	Field size (mm)	Penumbra left (mm)	Penumbra right (mm)	Field size (mm)	Penumbra left (mm)	Penumbra right (mm)
Varian linac – Eclipse (N=13)						
Film	21.7 ± 0.5	4.0 ± 0.4	4.1 ± 0.5	19.7 ± 0.1	3.2 ± 0.1	3.1 ± 0.1
TPS	21.2 ± 0.6	3.2 ± 0.4	3.2 ± 0.4	19.5 ± 0.1	3.4 ± 0.4	3.4 ± 0.6
Millennium 120 MLC (N=8)						
Film	22.1 ± 0.2	4.3 ± 0.2	4.4 ± 0.2	19.7 ± 0.1	3.2 ± 0.1	3.2 ± 0.0
TPS	21.5 ± 0.5	3.3 ± 0.5	3.4 ± 0.4	19.5 ± 0.1	3.4 ± 0.4	3.5 ± 0.5
HD 120 MLC (N=5)						
Film	21.1 ± 0.2	3.6 ± 0.3	3.5 ± 0.2	19.6 ± 0.1	3.2 ± 0.0	3.0 ± 0.2
TPS	20.7 ± 0.2	3.0 ± 0.3	3.1 ± 0.3	19.5 ± 0.1	3.2 ± 0.5	3.4 ± 0.7
Elekta linac – Monaco/Xio (N=5)						
Film	20.9 ± 0.8	5.5 ± 0.4	5.8 ± 0.3	19.9 ± 0.6	3.4 ± 0.3	3.4 ± 0.4
TPS	20.3 ± 0.4	5.0 ± 0.7	5.0 ± 0.5	20.2 ± 0.1	3.6 ± 0.1	3.6 ± 0.1
MLCi/MLCi2 (N=3)						
Film	21.5 ± 0.3	5.4 ± 0.4	5.9 ± 0.2	19.7 ± 0.6	3.2 ± 0.0	3.2 ± 0.4
TPS	20.4 ± 0.6	5.1 ± 0.9	5.1 ± 0.8	20.2 ± 0.1	3.7 ± 0.1	3.7 ± 0.2
Agility (N=2)						
Film	20.2 ± 0.1	5.6 ± 0.5	5.6 ± 0.5	20.1 ± 0.6	3.7 ± 0.3	3.7 ± 0.3
TPS	20.1 ± 0.1	4.9 ± 0.1	4.9 ± 0.1	20.3 ± 0.0	3.6 ± 0.0	3.6 ± 0.0

Measured transmission was on average 2.7 ± 0.2% (1SD) for linacs equipped with Varian Millennium 120 MLC (N=9), 2.3 ± 0.2% (1SD) with Varian HD120 MLC (N=5), 1.8 ± 0.0% (1SD) with Elekta MLCi (N=2) and 1.2 ± 0.0% (1SD) with Elekta Agility (N=2). Transmission was not measured in the centre equipped with MLCi2 as it was not possible to withdraw the X backup jaw.

Output check

The audit measurements at each centre started by the verification of daily output as calculated on TPS. Generally a good agreement was observed. The percent difference between calculated – 2 Gy – and measured doses was on average -0.6% ± 0.9% (1SD), varying from -2.4% to 0.8% – Figure 8. The tolerance level of ±2% is represented by the red lines.

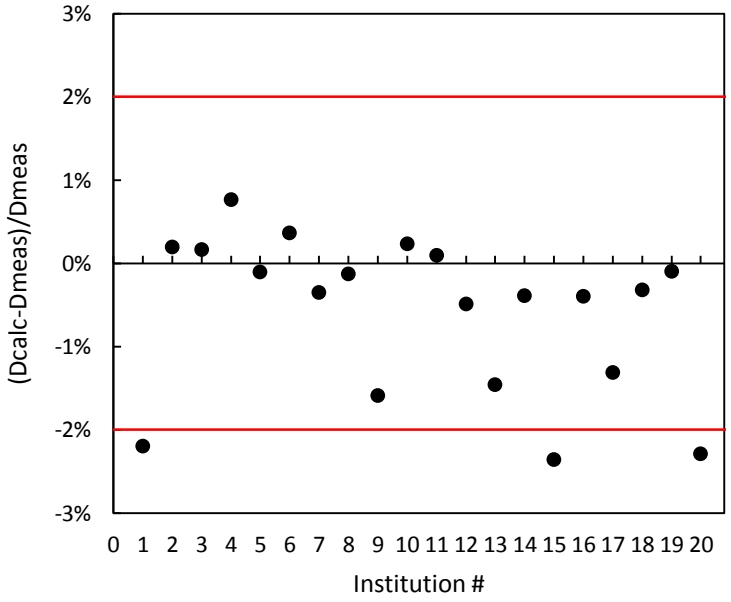

Figure 8 – Percent dose difference between calculated dose on TPS – 2 Gy – and measured dose in each centre.

Three centres had a difference in output out of tolerance. The causes were investigated while the auditor was still on-site. Recommendations were given accordingly. Beam output fluctuation on the audit day was taken into account for the subsequent measurements of the SHANE phantom.

IMRT measurements in SHANE phantom

In total 20 plans were verified using a common dosimetric system and evaluation metrics. Percent differences between calculated doses corrected by the daily ouput – D_{calc*} – and measured dose for "IC_PTV_7000", "IC_PTVn1_6000", "IC_PTVn2_5400" and "IC_SpinalCord" are presented in Figure 9.

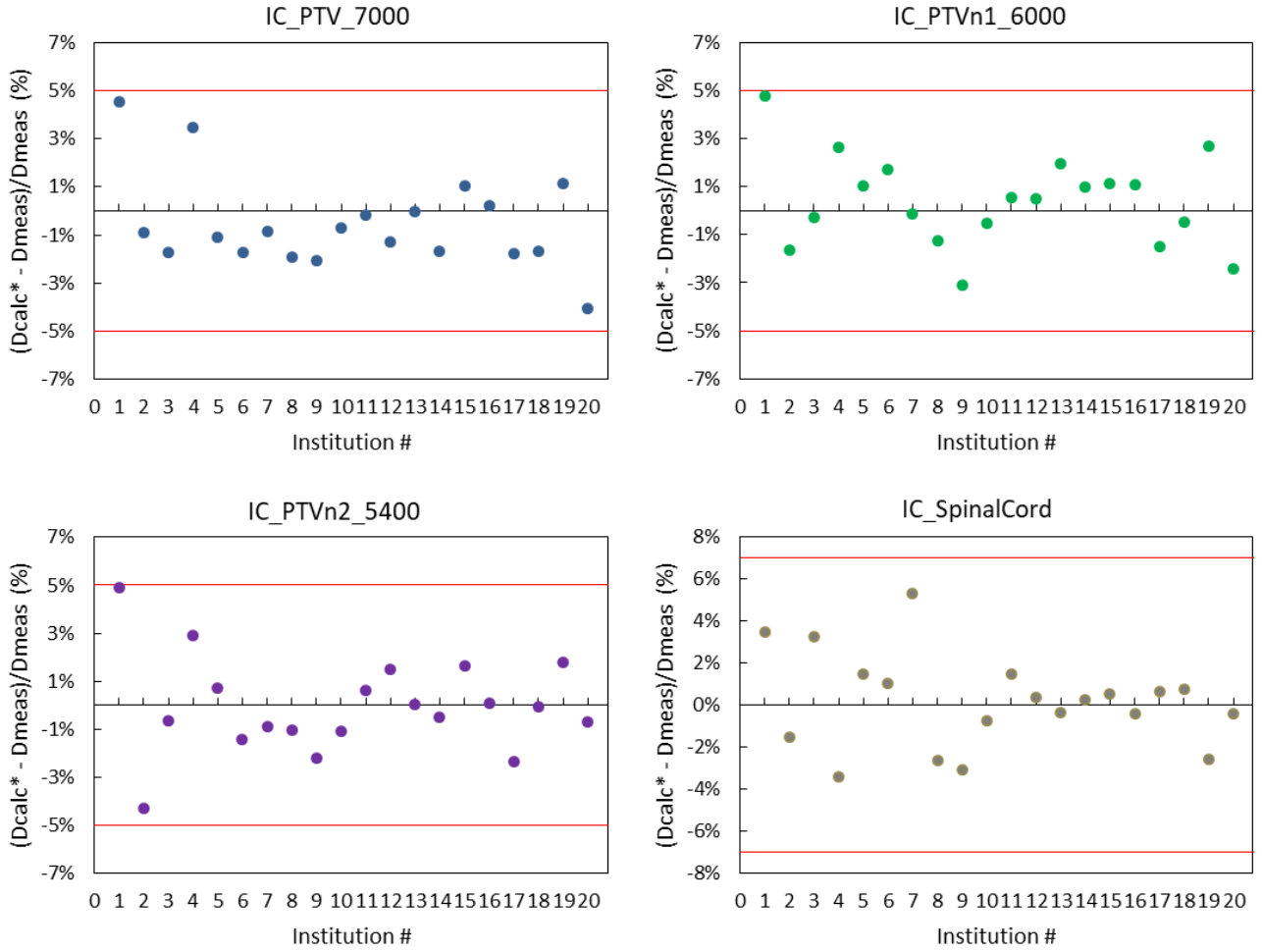

Figure 9 – Percent dose difference between calculated dose corrected for daily output variation – D_{calc*} – and measured dose for "IC_PTV_7000", "IC_PTVn1_6000", "IC_PTVn2_5400" and "IC_SpinalCord". The red lines represent the acceptance limit of of ±5% in PTVs and ±7% in organ-at-risk.

As it can be seen, individual results of all centres were within the established tolerances of ±5% for PTVs and ±7% for the spinal cord. Moreover, most centres had results within ±3% for all measurements points. The differences between ionization chamber measurements and calculated doses were on average -0.6 ± 2.0% (1SD) in the measurement point "IC_PTV_7000", 0.4% ± 1.9% (1SD) in "IC_PTVn1_6000", -0.1 ± 2.0% (1SD) in "IC_PTVn2_5400" and 0.2 ± 2.2% (1SD) in "IC_SpinalCord". 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.

Considering the results of film analysis, for global gamma criteria of 3%/3mm with 20% threshold, passing rates were on average 96.9 ± 2.9% (1SD), ranging from 90.3% to 99.1%. All have been above the acceptance limit of 90%. The gamma passing rates obtained by institution are presented in Figure 10. The tolerance level of 90% is represented by the red line.

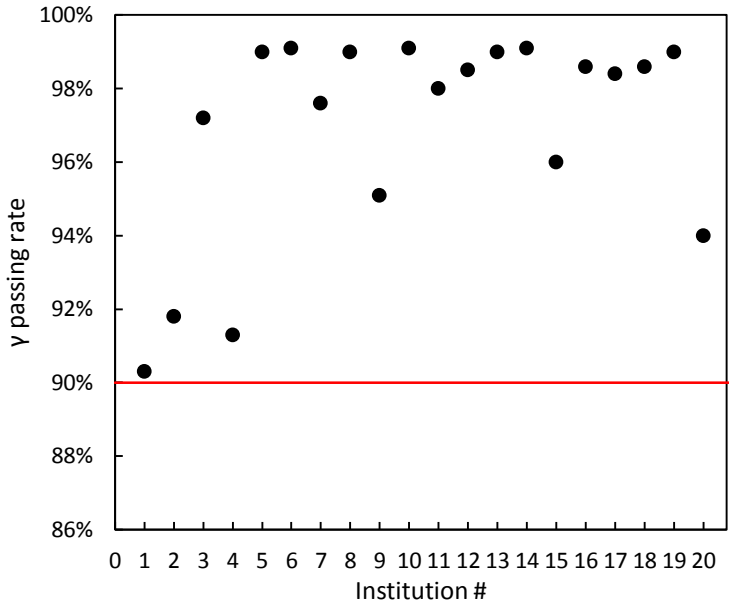

Figure 10 - Gamma passing rates (3%/3mm, 20%TH) per institution.

FilmQA Pro uses TPS as the reference dose distribution, which implies that the film dose map adopted the resolution of TPS dose grid. Therefore, dose distributions at the coronal plane corresponding to film were exported at a resolution of about 1 mm in all institutions, when possible. In institution #4 it was not possible to do so, therefore, the 3D matrix was used, being the considered pixel size ≈ 2.5 mm x 2.5 mm. In institution #2, a similar limitation was faced. The poorer results for these centres in Figure 10 may be partially related with this.

To further investigate the correlation between ionization chamber (IC) deviations and film gamma passing rates, an average ionization chamber percent deviation was calculated considering all four measurement points:

$$\frac{1}{4}\left[\left(\frac{|D_{cal}^{*}-D_{meas}|}{D_{meas}}\right)_{PTV\_7000}+\left(\frac{|D_{cal}^{*}-D_{meas}|}{D_{meas}}\right)_{PTV_{n1}\_6000}+\left(\frac{|D_{cal}^{*}-D_{meas}|}{D_{meas}}\right)_{PTV_{n2}\_5400}+\left(\frac{|D_{cal}^{*}-D_{meas}|}{D_{meas}}\right)_{SpinalCord}\right] \quad (2)$$

As it can be seen in Figure 11 a) the correlation is evident: there is clearly a group of centres where better γ passing rates (over 95%) correspond to lower IC measurement deviations (< 3%). However, when calculating IC average difference in this way, the spinal cord is given the same weight as PTVs, disregarding that "IC_SpinalCord" is a particular measurement point which is located in a low dose high gradient region. Thus, a second average IC deviation was calculated excluding this point. When considering only PTVs, the separation between two groups of results is even more evident – Figure 11 b). The group of centres with better γ passing rates with even lower IC deviations (< 2%) is clearly separated from the one with poorer film and IC results. The unique exception is in the upper right quadrant in Figure 11 b) with a border line passing rate of 95.1%.

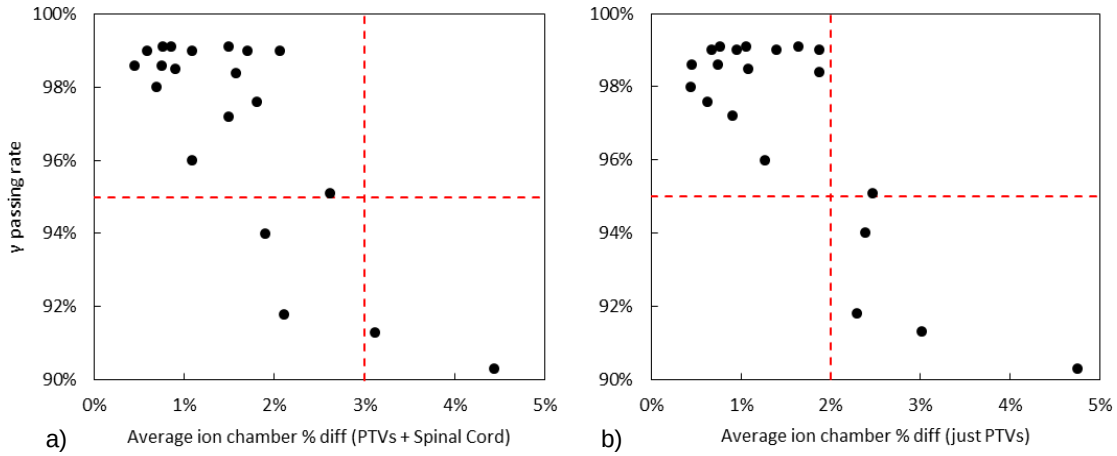

Figure 11 – Correlation between film γ passing rates and average absolute IC chamber deviations: a) including all four IC measuring points; b) excluding spinal cord measurement point.

Some common issues either per se or in combination may have contributed for the results of the centres with film gamma pass rate < 95% and average dose difference in PTVs > 2% (lower right quadrant in Figure 11 b). Those 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 CPs than other centres using the same treatment technique;
- Inclusion of treatment couch: 3 of these centres did not account for treatment 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 centres 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, as explained above;
- Small beam dosimetry modelling in TPS: in 2/4 centres, output factors for 3 x 3 cm^2 and 2 x 2 cm^2 field sizes were out of tolerance;
- Other factors may include experience 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 much time to perform the pre-visit activities on time and inherent audit preparation.

It must be stressed that pre-treatment QA verification had not predicted poor results in none of the centres.

The audit results were sent to all centres. An image of the scanned film, gamma map and three profiles: one in-plane, one cross PTV_7000 and another cross spinal cord were included. An example is presented in Figure 12.

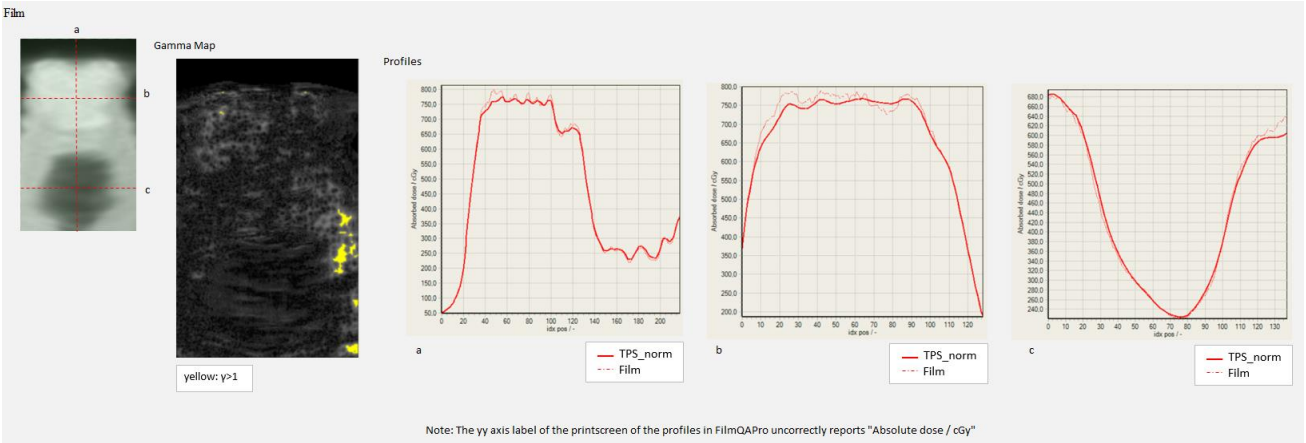

Figure 12 - Example of the reported results.

4| Conclusions and recommendations

The IMRT audit supported by the IAEA carried out in Portugal between March and September 2018 had 100% participation of the radiotherapy centres performing IMRT treatments. It certainly contributed to increase the confidence of all professionals involved and to strength the scientific cooperation among the medical physics national community.

Overall results of tests to check basic small field dosimetry data and MLC performance showed a good compliance with the established tolerances.

Regarding the reference dosimetry and corresponding daily output check some recommendations have been given. For instance, calculations of the dose calibration in reference conditions when using Monte Carlo should be carefully assessed in TPS (statistic uncertainty, dose grid, etc). Attention should also be paid to the conversion factors solid water-water provided by the RW3 slab phantom manufacturers. They should not be applied directly without being measured following a reference dosimetry protocol such as TRS 398.

The presented H&N clinical case allowed to test the institutions capabilities of performing IMRT treatments, even though the clinical scenario (dose prescription, structures set, objectives and constraints) may not correspond exactly to the local protocol. Couch inclusion in the TPS planning and calculations was only applied in 9/20 institutions. This might not have a large influence on dose distribution for head and neck cases, but it may have a significant dosimetric impact depending on the tumour location, beam energy and treatment technique [17].

Generally, the audit programme was considered demanding due to the amount of tasks to perform. The re-optimization of the SHANE IMRT H&N plan was also time consuming. However, time spent at each institution also depended much on the effort put on pre-visit activities and inherent preparation.

The audit results confirmed that the status of TPS calculations and dose delivery for H&N IMRT in Portugal is globally within reference standards with no major reasons of concern.

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Appendix A

WORKSHOP

Scientific Program

09:00-09:30	**Registration**
09:30-10:00	**Opening session** Maria Esmeralda Poli (DFM), Pedro Vaz (IST), Carlos Santos (IPOCFG)
	Morning session Chairs: Maria Esmeralda Poli (DFM), Maria do Carmo Lopes (IPOCFG)
10:00-10:30	Small Field Dosimetry – IAEA/AAPM code of practice Maria do Carmo Lopes (IPOCFG)
10:30-11:00	New tools for plan quality assessment Tiago Ventura (IPOCFG)
11:00-11:30	**Coffee break**
11:30-12:00	IAEA supported national IMRT audit – the methodology Tânia Santos (FCTUC)
12:00-12:30	IAEA supported national IMRT audit – practical considerations and results of pilot study Eduard Gershkevitsh (IAEA)
12:30-14:00	**Lunch break**
	Commercial symposium Chair: Miguel Capela (IPOCFG)
14:00-14:10	Avanço
14:10-14:20	Bioterra
14:20-14:30	ABGT
14:30-14:40	Interphysix
14:40-14:50	Ibervoxel
15:00-16:30	**Hands-on sessions** I – SHANE irradiation in Tomotherapy | Maria do Carmo Lopes, Tânia Santos II – SHANE planning | Josefina Mateus, Miguel Capela III – Practical cases in SpiderPlan and PlanIQ | Tiago Ventura
16:30-17:00	**Coffee break**
17:00-17:30	**Wrap-up: Questions, discussion and conclusion** Eduard Gershkevitsh (IAEA), Maria do Carmo Lopes (IPOCFG)