



Technical note

End-to-end test for lung SBRT: An Italian multicentric pilot experience

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ARTICLE INFO

Keywords:

Lung SBRT

End-to-end test

QA

ABSTRACT

Purpose: Set up a lung SBRT end-to-end (e2e) test and perform a multicentre validation.

Material and methods: A group of medical physicists from four hospitals and the Italian Institute of Ionizing Radiation Metrology designed the present e2e test. One sub-group set up the test, while another tested its feasibility and ease of use. A satisfaction questionnaire was used to collect user feedback.

Each participating centre (PC) received the ADAM breathing phantom, a microDiamond detector and radiochromic films. Following the e2e protocol, each PC performed its standard internal procedure for simulating, planning, and irradiating the phantom. Each PC uploaded its planning and treatment delivery data in a shared Google Drive. A single centre analyzed all the data.

Results: The e2e test was successfully performed by all PCs. Participants' comments indicated that ADAM was well suited to the purpose and the protocol well described. All PCs performed the test in static and dynamic modes. The ratio between measured and planned point dose obtained by PC1, PC2, PC3, PC4 was: 0.99, 0.96, 1.01 and 1.01 (static track) and 0.99, 1.02, 1.01 and 0.94 (dynamic track). The gamma passing rates (3 % global, 3 mm) between planned and measured dose maps were 98.5 %, 94.0 %, 99.1 % and 94.0 % (static track) and 99.5 %, 96.5 %, 86.0 % and 94.5 % (dynamic track) for PC1, PC2, PC3 and PC4, respectively.

Conclusions: An e2e test for lung SBRT has been proposed and tested in a multicentre framework. The results and user feedback prove the validity of the proposed e2e test.

Introduction

Lung Stereotactic Body Radiation Therapy (SBRT) is a technique that requires sophisticated technology capable of treating patients with large fractions of highly conformal doses. The short SBRT treatment schemes, where inaccuracies during one fraction cannot easily be compensated in the remaining fractions, require the technology used for treatment delivery to guarantee high geometric precision and dosimetric accuracy [1,2].

Dosimetry audits can support users to safely implement advanced treatment modalities and techniques [3–5]. They have the potential to verify whether the quality of dosimetry practices is adequate [6–7] and they are an effective way of identifying issues that may cause harm to patients. Dosimetry audits also play a significant role in highlighting differences between patients treated for the same disease within multi-institutional trials [8–9] and they contribute to the standardization of radiotherapy procedures. Several types of dosimetric audits are available, from the simplest, a postal TLD audit, to the most complex, an end-

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<https://doi.org/10.1016/j.ejmp.2022.11.004>

Received 29 January 2022; Received in revised form 13 September 2022; Accepted 5 November 2022

Available online 16 November 2022

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to-end (e2e) test performed during on-site visits [8]. Anthropomorphic phantoms that follow the same patient pathway, from imaging to dose distribution delivery, are generally used in e2e tests. Access to dosimetry audits is not easily available in all countries [10]. Only a few organizations: the IAEA jointly with the World Health Organization, the Imaging and Radiation Oncology Core Houston QA Centre, together with the Radiation Dosimetry Service (Houston, USA) and EQUAL-ESTRO (Villejuif, France), provide external dosimetry auditing and verification services for advanced radiotherapy machines and techniques worldwide [10]. Updated information on dosimetry audits can be found on the dosimetry audit network (DAN) website [11].

To support medical physicists in handling technical and dosimetric aspects of SBRT, the Italian Association of Medical Physicists created a working group (WG) on this issue in 2013 named AIFM/ SBRT-WG. One hundred and fifty-seven medical physicists from more than eighty Italian centres participated in SBRT-WG initiatives in 2021 [12].

The idea of designing an e2e test for lung SBRT originates within the framework of this SBRT-WG. The Italian National Institute of Ionizing Radiation Metrology and four teams of medical physicists working in Italian hospitals collaborated to set up a lung SBRT e2e test. The final protocol and the results of the e2e test are reported together with user feedback collected through a satisfaction questionnaire.

Compared to previously published papers reporting on SBRT e2e experiences [7,13,14], the protocol we propose involves the use of a more realistic breathing anthropomorphic phantom.

The verisimilitude of the phantom makes it possible to test all aspects of the patient treatment including dosimetry, motion management, target volume definition and patient positioning.

Our proposal aims to perform a complete e2e test from CT image acquisitions to plan delivery verifications, including all image-guided radiation therapy (IGRT) aspects employed.

The main objective of this experience was to establish a robust procedure to assess the consistency between planned and measured doses in lung SBRT to be proposed to other radiotherapy centres. We

think that this protocol, shared among centres equipped with different machines and using different planning approaches, can encourage other centres to carry out similar experiences.

Materials and methods

The phantom

It is a shared opinion that for an e2e test the greater the resemblance of the phantom to the patient, the easier it is to simulate the whole clinical process [8]. For this reason, we selected the ADAM phantom, which has previously been described in detail [15,16], for its anthropomorphic shape, lifelike breathing, and capability to work with any respiratory synchronization device. Briefly, ADAM is an anthropomorphic breathing phantom (Fig. 1), 60 cm long and weighting 12 kg. It consists of a 3D printed human torso with moving upper chest wall and lungs. The central phantom region (with realistic embedded ribs and spinal cord) was printed with a 100 % infill density to obtain a realistic soft tissue approximation ($HU = 100 \pm 20$) [15]. The lungs (made of two blocks of cork) contain four structures simulating lung tumours (LTs) and can host radiochromic films and a micro-diamond detector (in LT4). The cork block containing LT1 is composed by two halves. The upper half can be lifted and repositioned on the lower one thanks to four small wooden pins attached to the blocks end. Four alignment markers are enclosed in the lower half around LT1. These markers, visible in the CT coronal plane, are also used to mark and align films. The coordinates of alignment markers are copied on the dose map and used to register planned and measured dose data.

Four linear actuators, driven by an Arduino board, move the lungs and the upper chest wall.

For the e2e test, we used a patient-specific breathing signal (14 breaths per minute max) and a linear path for the LTs with a maximum excursion of 2.5 cm. Dose distribution and point dose measurements were performed on LT1 and LT4, respectively.

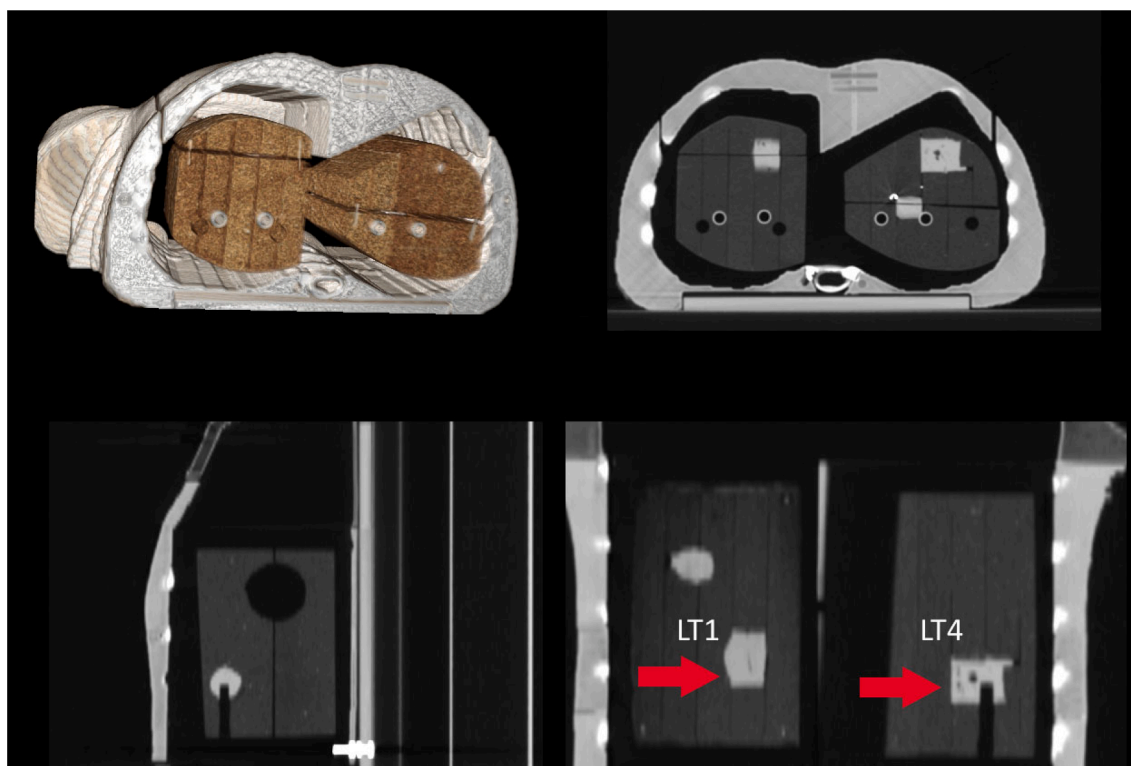


Fig. 1. 3D view and axial, sagittal and coronal reconstructions of an ADAM CT study. In the coronal view, the lesions LT1 (3.6 cm superior-inferior (SI), 2.4 cm latero-lateral (LL), 2.7 cm anterior-posterior (AP)) and LT4 (2.5 cm SI, 3.0 cm LL, 2.6 cm AP) used for this e2e protocol are shown.

A video tutorial on phantom usage and ADAM CT images were shared among PCs to allow users to familiarize themselves with how to use the phantom before carrying out the e2e test.

Detectors

Point dose measurements in LT4 were carried out with a 60019 microDiamond detector (PTW Freiburg, Germany) characterized in a reference ^{60}Co gamma beam available at the Italian National Institute of Ionizing Radiation Metrology. Mainly, angular dependence and long term reproducibility of the detector response were assessed and the absorbed dose calibration factor traceable to the Italian absorbed dose to water primary standard was determined with a combined standard uncertainty of 0.7 %. Detector calibrations performed at beginning and end of the multicenter e2e tests showed a variation of 0.8 % in the detector response. Then, considering a rectangular distribution centered on an extreme, the uncertainty associated to the long term reproducibility was placed at 0.5 %. For calibration, the microDiamond was irradiated with its main axis placed at the reference depth, perpendicular to the beam axis in such a way to reproduce the radial beam incidence as in the ADAM phantom for the e2e test and to minimize effects due to the detector angular response. The radial angular dependence was evaluated in the calibration beam rotating the microDiamond around its main axis always perpendicular to the beam axis. The associated standard uncertainty resulted 0.3 %. Differences in the energy distributions between the calibration and clinical beams can affect the microDiamond response in e2e point dose measurements. In the literature variations in the microDiamond response between ^{60}Co and 6 MV beam qualities have been reported in the range 0 % to about 2 % [17,18]. However, no consensus values for the beam quality correction factors are available, therefore for the e2e absorbed dose determinations the beam quality factor was assumed to be unity with a relative standard uncertainty of 1 % (1SD). Then the combined standard uncertainty in the point dose determination was estimated to be 1.7 % (1SD), considering the above mentioned components (detector calibration (0.7 %), energy dependence (1 %), radial angular dependence (0.3 %), long term reproducibility (0.5 %)) and additional contributions due to dose rate dependence (0.7 %), dose linearity (0.5 %) and electrometer calibration and stability (0.5 %). The figures 0.7 % and 0.5 % associated to dose rate dependence and dose linearity were derived from Reggiori et al [19]. Firstly, a range of variability for the detector response was estimated according to the dose and dose rate range pertaining to the e2e tests. Then, the uncertainty components were stated assuming a rectangular distribution within the estimated range of variability. Lastly, the figure 0.5 % associated to the electrometer was a conservative estimate that includes the nominal long term stability of a clinical instrument.

Dose distribution measurements in LT1 were made using Gafchromic EBT3 films (Ashland Inc., Wayne, NJ). Film reading and analysis was done in a single centre using the FILMQA™ software (Ashland Inc., Wayne, NJ) and a shared procedure based on a multichannel approach [20]. Films were scanned in red–green–blue format using an Epson Expression 10000XL scanner (Seiko Epson Corporation, Nagano, Japan) with signal resolution of 16 bits and spatial resolution of 72 dpi. For the conversion of the pixel value into absorbed dose a calibration curve was obtained for each of the three channels (red, green and blue) using the data fitting function $X(D) = a + b/(D-c)$ where $X(D)$ is the pixel value at the dose D for the channel X and a, b and c are constants. For calibration, pieces of EBT3 films were exposed to absorbed dose in the range 1–30 Gy. The films were irradiated in a 10.4 cm × 10.4 cm field at 10 cm depth in solid water with a 6 MV photon beam produced by an Elekta accelerator. The irradiation dose was determined by means of a Farmer ionization chamber, type NE 2571, calibrated in terms of absorbed dose to water at the Italian National Institute of Ionizing Radiation Metrology. For dose distribution determination the calibration curve is scaled by means of reference films scanned simultaneously with the measurement films.

Each participating centre (PC) received the phantom, the microDiamond detector, and a film kit for the dosimetry tests. The film kit consisted of two labelled films (marked for alignment purposes), cut to fit comfortably in the right lung and two reference strips. The reference strips were used for adapting film calibration [20] and had to receive a dose between 80 % and 100 % of the maximum expected dose. All films belonged to the same batch. The film analysis was performed by aligning the measured and calculated dose grids using the phantom alignment markers (accuracy estimated 1 mm).

e2e protocol

The proposed e2e protocol is composed of a Static and a Dynamic track that characterise phantom acquisition, planning and treatment delivery mode. To verify the protocol robustness, the medical physicists who participated in drafting the protocol did not take part in the measurement sessions.

Phantom simulation

The phantom acquisition consisted of the following steps: a *Static track* in which a CT study of the static phantom was acquired with the standard protocol used in each institution; a *Dynamic track* in which the phantom was turned on and a 4DCT study (or a Slow CT) carried out with the standard protocol used in each institution. For both the static and dynamic tracks, the centres were asked to apply the same procedures (reference points, virtual simulation, etc.) to the phantom that they would on a patient.

Planning

For the *Static track*, the Gross Tumor Volumes GTV-LT1 and GTV-LT4 were defined on the static CT for both LT1 and LT4. For the *dynamic track*, the Internal Tumor Volumes ITV-LT1 and ITV-LT4 were defined on the 4DCT series (or slow CT) for both LT1 and LT4, based on the Centre's internal method of accounting for respiratory motion. The following Organs At Risk (OAR) were segmented on both series: spinal cord, chest wall, lungs and heart. The Planning Target Volumes (PTV-LT1, PTV-LT4) were defined by expanding the two GTVs (or ITVs in the case of the dynamic track) with an isotropic 0.5 cm margin.

Two plans for treating the PTV-LT1 and the PTV-LT4 (54 Gy/3 fractions) were optimized with the treatment technique that reflects the PC clinical practice in accordance with the following constraints:

- at least 98 % of the PTV must receive 54 Gy;
- keep a uniform ($V107\% < 2\%$) dose prescription inside the PTV- LT4 (to prevent the detector measurement region from falling into a high dose gradient);
- both uniform and inhomogeneous dose distributions are allowed on the PTV-LT1;
- hotspots are allowed only within the PTVs;
- use constraints reported in Table 1 (UK consensus guideline [21]).

Dose delivery

Before starting the delivery session, the routine pre-treatment quality assurance (QA) of both static and dynamic plans was performed by each

Table 1

OARs requirements for the lung SBRT plans in 3 fractions. V_{XGy} = volume receiving X Gy; D_{Xcm3} = dose to X cm³ of the considered organ.

Organ	Constraint	Optimal	Mandatory
Spinal canal (including medulla)	D_{max} (0.1 cm ³)	<18 Gy	<21.9 Gy
	D_{1cm3}	<12.3 Gy	–
Heart	D_{max} (0.5 cm ³)	<24 Gy	<26 Gy
Chest wall	D_{30cm3}	<30 Gy	–
Normal lungs	V_{20Gy}	–	<10 %
(lungs – gross tumor volume)			

centre. Furthermore, before starting the e2e test, the machine daily output was measured and the reference strips were irradiated with a dose between 80 % and 100 % of the maximum plan expected dose. The centres were asked to use multiple references if the maximum doses of the static and dynamic plans were significantly different or to choose a common value fitting all the irradiations.

Before irradiating PTV-LT4, ADAM position was controlled using the clinical IGRT protocol. Dose to PTV-LT4 was measured with the microDiamond detector. ADAM was then re-positioned to treat PTV-LT1 using the clinical IGRT protocol. After verifying its correct setup, radiochromic films, previously cut and marked, were aligned on the lower half alignment markers, secured with adhesive tape and sandwiched between the two block halves. The reproducibility of the phantom/film assembly was verified in a previous work [16] repeating the positioning and irradiation three times. The comparison between films, considering the first irradiation as reference, resulted in 100 % mean GI3%/3 mm and GI3%/2 mm (10 %th) for both static and dynamic tests.

e2e test logistics

ADAM, the microDiamond detector, and a film kit for the dosimetry tests were shipped to each PC together with the dosimetric protocol and instructions for using ADAM. After completing the test, each PC returned the material with the irradiated films to the centre performing the analysis.

To simplify data exchange, a Google Drive containing instructions, video tutorials for ADAM usage and folders to upload data, was shared among PCs. Each PC uploaded ADAM CT studies, RTDose, RTStructures and RTPlans of all prepared plans, filled in the Institution Information Report (Supplementary material – SBRT e2e test – Institution Information Report) and answered the Institution Satisfaction Questionnaire (Supplementary material – SBRT e2e test – Institution Satisfaction Questionnaire).

Results

All PCs were successful in carrying out the e2e test. No user found any difficulty in using ADAM. All users stated that the phantom was well suited to the purpose and the protocol was well described. The breathing signal of the phantom was detected by all gating systems used for 4DCT acquisitions. Some users added comments in the Satisfaction Questionnaire, for example: “include a picture of the respiratory cycle in the documentation”, “assist users to identify heart position”, “give the user an estimate of the time needed to complete the e2e test”. Two centres stated they had previous dosimetric auditing experience using the IROC Houston lung phantom and insert with the mobile platform.

A report of the irradiation results analysis was provided to each centre and uploaded in the shared Google drive. (An example in the Supplementary material- SBRT e2e test - P2 report).

A summary of the equipment used and the SBRT approaches employed by each centre are reported in Table 2.

All PCs checked the linac output before the test, resulting in dose deviation from the expected value of <1 % for all PCs. All PCs tested the static and the dynamic tracks the same day, after performing their customary pre-treatment QA. Results of pre-treatment QA are reported in Supplementary material.

The results of the e2e test are reported in Table 3 which shows the ratio between measured (with microDiamond detector) and calculated dose in PTV-LT4 and the gamma passing rates between planned and measured (with films) dose distributions on PTV-LT1 of both static and dynamic tracks.

In Fig. 2 gamma maps and isodose curves of the static track irradiations performed by all PCs are reported.

In Fig. 3 the same data for the dynamic track irradiations are reported.

Finally, measured and calculated dose profiles on PTV-LT1 of the Static and Dynamic tracks are reported in Fig. 4.

Table 2

Summary of the equipment, planning approach and method to account for respiratory induced target motion of participating centres.

	PC1	PC2	PC3	PC4
Treatment Unit	Axesse Agility (Elekta)	Truebeam (Varian)	Synergy (Elekta)	Synergy BM (Elekta)
Technique	VMAT 6MV	VMAT 6MV FFF	VMAT 6MV	VMAT 6MV
Treatment Planning System	RayStation 9A (RaySearch)	Eclipse 15.5 (Varian)	Monaco 5.11 (Elekta)	Monaco 5.11 (Elekta)
Method to Account for Respiratory Induced Target Motion	CCC* 4DCT with pressure belt. ITV defined on 10 phases of 4DCT. AIP for planning. Treatment in free breathing.	AAA° v.15.5.12 4DCT with RPM° ITV defined on 7 phases of 4DCT. AIP for planning. Treatment in free breathing.	Monte Carlo 4DCT with Sentinel 4DCT°. ITV defined on 4 phases of 4DCT. AIP for planning. Treatment in free breathing.	Monte Carlo 4DCT with pressure belt. ITV defined on MIP. AIP for planning. Treatment in free breathing.

CCC* Collapsed Cone Convolution.

AAA° Anisotropic Analytical Algorithm.

4DCT Four-dimensional computed tomography.

ITV Internal target volume.

RPM° Real-time Position Management (Varian).

Sentinel 4DCT° Surface Scanning system (C-RAD).

AIP Average Intensity Projection.

MIP Maximum Intensity Projection.

Table 3

e2e test results. Comparison between planned and measured doses for the microDiamond detector and for the film dosimetry for each PC and for both static and dynamic irradiations.

PTV-LT4				
measured/calculated	PC1	PC2	PC3	PC4
static	0.99	0.96	1.01	1.01
dynamic	0.99	1.02	1.01	0.94
PTV-LT1				
gamma pass rate (3 %global, 3 mm/ threshold 10 %)				
static	98.5 %	94 %	99.1 %	94 %
dynamic	99.5 %	96.5 %	86 %	94.5 %

Differences in planning approach between PC1 and the other three PCs are visible. In the first case, the entire PTV-LT1 received 54 Gy; in the other cases, only 98 % of the PTV volume received 54 Gy (all respecting the planning protocol).

Discussion

In this paper, we reported the experience of a group of medical physicists from four Italian centres in developing an e2e test to evaluate the robustness of lung SBRT treatments. Lack of national audit programs carried out by independent organizations encouraged the design of this multicentre experience. The purpose of this work, in addition to a peer-to-peer comparison, was to develop a test that could be carried out, in future, by other medical physicists wishing to test their SBRT procedures. To achieve this, a sub-set of the group set up and fine-tuned all aspects of this e2e test (from the dosimetry protocol to logistics), while others tested its feasibility and ease of use. Their observations, aimed at improving this e2e test, were collected during this exploratory phase using a satisfaction questionnaire that investigated the phantom's ease of use, the protocol feasibility, and the reporting format. Such a multicentre pilot study of an e2e test is an important step to validate test

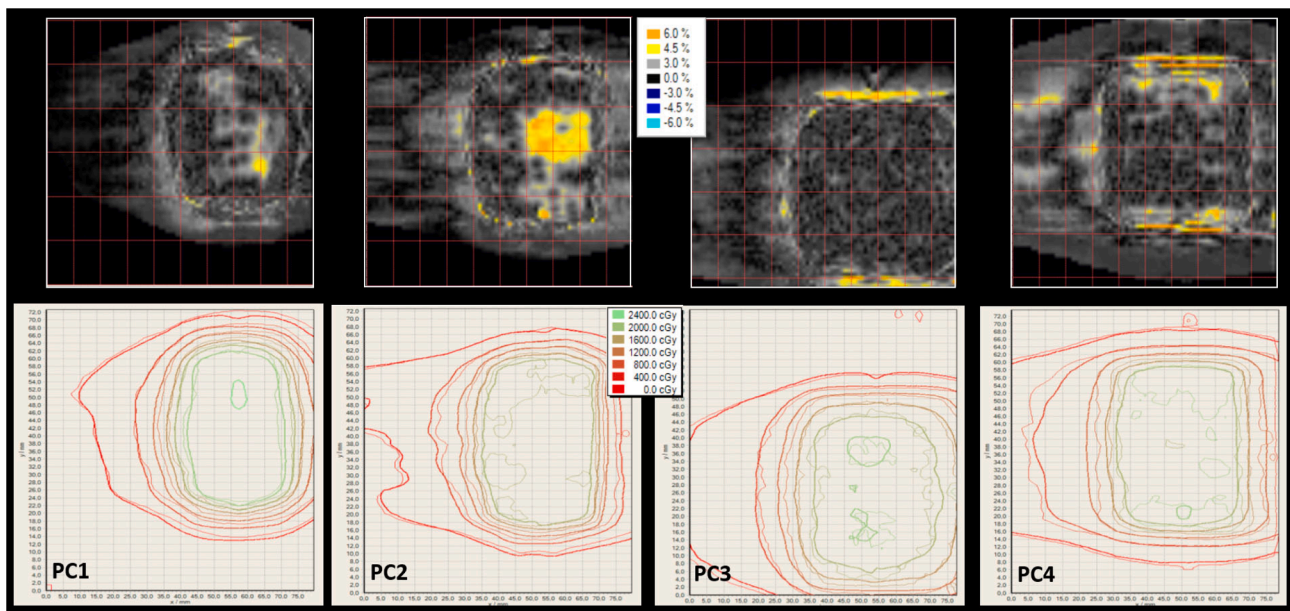


Fig. 2. Static track on PTV-LT1. The first row shows the gamma index map of the irradiations carried out by the four participant centres. The second row reports isodose maps. Bold and thin lines indicate measured and calculated doses, respectively. PC1, PC2, PC3 and PC4 indicate the four participating centres. The dose map of center 3 is translated compared to that of the other centers since the film was damaged to an edge (due to cut).

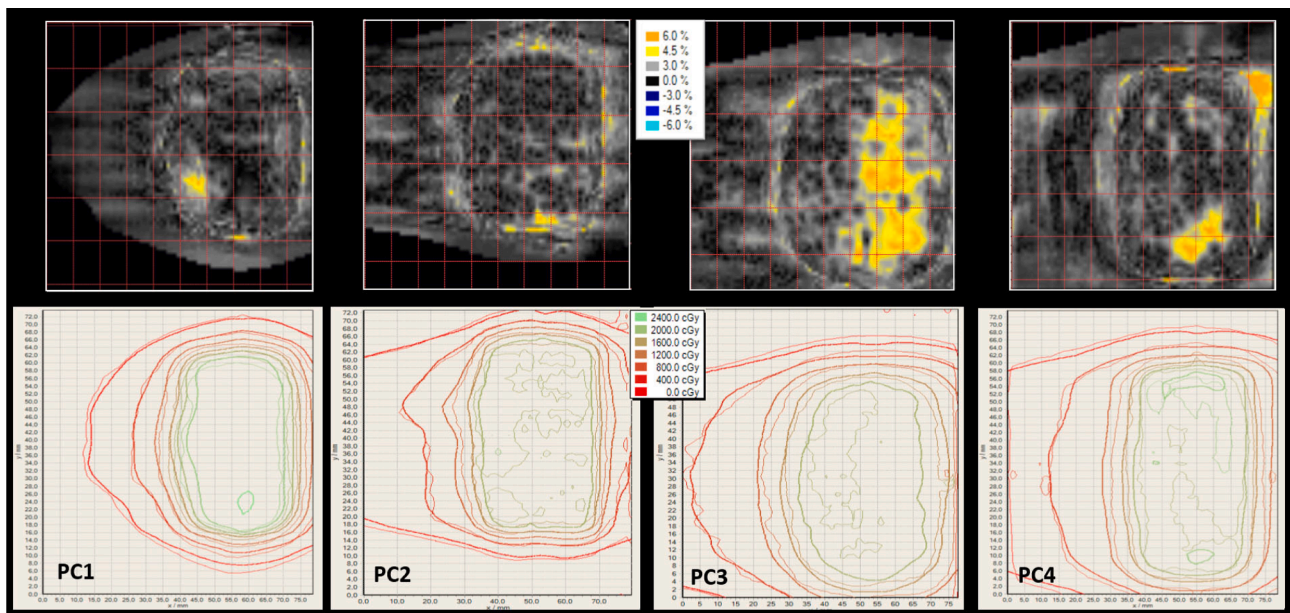


Fig. 3. Dynamic track on PTV-LT1. The first row shows the gamma index map of the irradiations carried out by the four participant centres. The second row reports isodose maps. Bold and thin lines indicate measured and calculated doses, respectively. PC1, PC2, PC3 and PC4 indicate the four participating centres.

design and implementation [22]. The preliminary e2e test results provided feedback on clarity and completeness of the instructions and data sheet and give an indication of the workload involved.

All users successfully employed ADAM and judged its anthropomorphic shape optimal to test SBRT procedures. One reported drawback is the difficult localization of the phantom's heart during the contouring phase. This issue might be solved by including some example data.

ADAM worked with several systems used for 4DCT respiratory gating (pressure belt, surface system and infrared tracking camera with a reflective marker placed on the patient) and allowed film dosimetry and real-time point dose measurements.

Due to the high spatial resolution, film dosimetry is considered ideal

for QA SBRT [23–25], but a considerable investment of time and resources is necessary for the data analysis. In contrast, point dose detectors allow real-time analysis and provide immediate results. Numerous point dose detectors can be used, but microDiamond has proven reliability and robustness for end-to-end dosimetry in SBRT and SRS applications [17].

Before carrying out the e2e test, all PCs performed a pre-treatment verification to assess the plan quality employing several detectors and evaluation metrics (see Supplementary document). For two centres using ArcCHECK (Sun Nuclear) detector, a direct comparison with results reported by the UK National Radiotherapy Trials Quality Assurance (RTTQA) Group [26] was possible. The RTTQA percentages of gamma

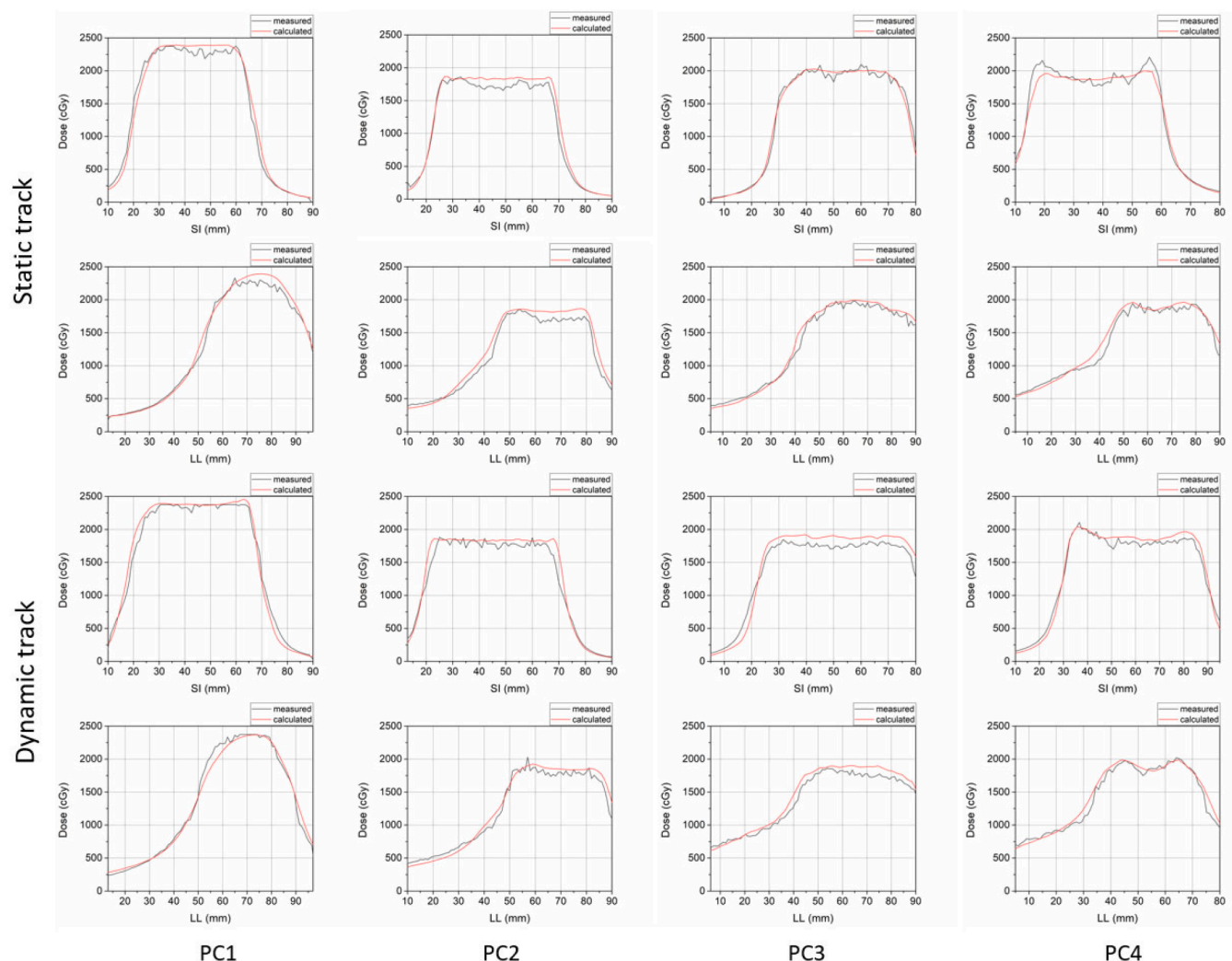


Fig. 4. In the first and second rows (static track), measured (black) and calculated (red) dose profiles at isocenter on PTV-LT1 along with the superior-inferior (SI) and latero-lateral (LL) directions, respectively, are reported. In the third and fourth rows (dynamic track), measured and calculated dose profiles at isocenter on PTV-LT1 along with the superior-inferior (SI) and latero-lateral (LL) directions, respectively, are reported. PC1, PC2, PC3 and PC4 indicate the four participating centres.

passing rate tolerances were satisfied in both cases.

For the e2e test, we investigated both static and dynamic modalities. For the static track, median and range deviations between planned and measured point dose and gamma passing rates over the 4 PCs were 0 % [−4% to 1 %] and 96.25 % [94 % to 99.1 %], respectively. For the dynamic track, the approach followed by PCs in the ITV definition was not always the same. PC1, PC2 and PC3 enveloped the CTVs drawn on each phase of the 4DCT to generate the ITV, PC4 used the Maximum Intensity Projection image.

For the dynamic track, median and range point dose deviations and gamma passing rates over the 4 PCs were: 0 %, [−6% to 2 %] and 95.5 % [86.0 % to 99.5 %], respectively.

Several multicentre studies on the same topic, using static [7] or dynamic [13,14] phantoms, have been published recently. Distefano et al. [7] used a CIRS IMRT thorax phantom (CIRSinc, USA) with film and alanine detectors to perform a national audit on twenty-seven centres. Their results (static irradiations) showed median and range deviations between the calculated and measured dose of 0.6 % (−6.1 % to 3.2 %) for alanine and of 80.1 % (52.9 % to 97.1 %) for the percentage of gamma passing rate (3 % local, 2 mm, 50 % prescription dose threshold) for EBT3 films. Palmer et al. [13] audited twelve centres with a QUASAR (Modus Medical Devices Inc., Canada) respiratory motion lung-phantom equipped with a custom-designed insert performing static and dynamic

tests. In their study, a longitudinal target path (sinusoidal, ± 7 mm –15 breaths per minute), was used for the dynamic test. Their results showed median, lower, and upper quartiles of the gamma passing rates (3 % global, 3 mm, threshold 20 %) between TPS-calculated and film-measured doses were 99.4 % (98.7 % to 99.8 %) and 96.1 % (94.1 % to 98.2 %) for the static and dynamic tracks, respectively.

Lambrecht et al. [14] performed static and dynamic e2e tests in sixteen centres using a CIRS (CIRSinc, USA) dynamic thorax phantom. The dynamic track was tested on a sphere (7.5 mm radius) moving according to a $\cos^6$ function with a period of 3 s and a 15 mm peak-to-peak amplitude. In their study, the median and range, between measured and point-planned dose, was 1.8 % [−0.1 % to 6.7 %] and 3.2 % [−3.2 % to 15.7 %] in static and dynamic situations, respectively. Median and range gamma passing rates were 92.0 % [68.0 %, 99.0 %] and 71 % [40.0 %, 95.0 %] for static and dynamic mode, respectively. Compared to the data reported by Palmer and Lambrecht, our sample is smaller, but the results were consistent with theirs. As expected, the static tests resulted better than the dynamic tests. The gamma passing rate median values were close to those reported by Palmer et al. [13] and slightly higher than those of Lambrecht et al. [14]. A limitation of our work is the lack of an estimate of the uncertainties associated with the use of EBT3 films in the range of doses employed in this work which will be the subject of future studies. Palmer et al [27] reported that the use of EBT-XD films

demonstrated moderately improved gamma passing rates and isodose line agreements over EBT3, for typical SRS treatment delivery.

Finally, we observe that, in our case, no participant made significant phantom positioning errors detectable from the displacement of the calculated and measured profiles. This is an interesting finding considering that from the failure analysis of 1052 irradiations performed with the anthropomorphic IROC phantom [28], around 6 % of the total irradiations failed due to a positioning error. Even though our sample is so small that a comparison with the results obtained using the IROC phantom is not possible, we observe that the implementation of the ADAM and IROC phantom breathing movements are different. The IROC phantom is placed on a moving platform to simulate breathing, while in ADAM the breathing movement is achieved by moving only the lungs and the upper thorax while leaving the lateral parts of the thorax, where the alignment markers are attached, stationary. In our opinion, the immobility of the alignment markers makes the phantom alignment much easier.

Conclusions

An e2e test for lung SBRT has been proposed and tested in a multicentre framework to demonstrate the feasibility of the entire procedure. The results and user feedback prove the test's validity. We think that the presented e2e test can be a useful starting point for other centres wishing to assess their SBRT procedures. Moreover, this multicentre study can also be considered a hopeful step towards a national dosimetry audit program on advanced radiotherapy techniques within a collaboration between the AIFM and ENEA.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ejmp.2022.11.004>.

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