Development of phantom and methodology for 3D and 4D dose intercomparisons for advanced lung radiotherapy

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Abstract. There are few reported intercomparisons or audits of combinations of advanced radiotherapy methods, particularly for 4D treatments. As part of an evaluation of the implementation of advanced radiotherapy technology, a phantom and associated methods, initially developed for in-house commissioning and QA of 4D lung treatments, has been developed further with the aim of using it for end-to-end dose intercomparison of 4D treatment planning and delivery. The respiratory thorax phantom can house moving inserts with variable speed (breathing rate) and motion amplitude. In one set-up mode it contains a small ion chamber for point dose measurements, or alternatively it can hold strips of radiochromic film to measure dose distributions. Initial pilot and feasibility measurements have been carried out in one hospital to thoroughly test the methods and procedures before using it more widely across a range of hospitals and treatment systems. Overall, the results show good agreement between measured and calculated doses and distributions, supporting the use of the phantom and methodology for multi-centre intercomparisons. However, before wider use, refinements of the method and analysis are currently underway particularly for the film measurements.

1. Introduction

As part of an evaluation of the consistency and accuracy of the implementation of advanced radiotherapy (RT) technology for the NSW Health Department, the Institute of Medical Physics (IMP) and a clinical partner, the Prince of Wales Hospital (PoWH), have developed and tested a phantom for end-to-end dose intercomparison of planning and ‘treatment’ delivery for lung radiotherapy, aimed at including IMRT, VMAT, hypo-fractionated SBRT, 4D RT and the use of FFF beams, across a range of treatment planning systems (TPSs), delivery systems and techniques. There are few, or no, reported audits/intercomparisons of many of these combinations [1-3], thus this work is aimed at providing initial testing of potential audit methods, with the developments linked with the Australian RT clinical trials (TROG) QA group [3] and the Australian national RT dosimetry audit system (ACDS:ARPANSA) [3, 4].
2. Materials and Methods

2.1 The phantom and measuring systems

The respiratory phantom was originally designed in-house at PoWH as a QA and verification tool for local 4D treatment commissioning and QC, based on single point ion chamber measurements and to fulfill the requirement for strict QA for 4D methods [5]. It was then further developed for wider use with different systems in different centres and to contain radiochromic film for dose distribution measurements. The phantom (figure 1) was to be representative of the thorax and was constructed of water-substitute plastic, with lung-substitute plastic to form two lungs. In the original version, one of the lungs contained a small cylindrical water-equivalent 'lung tumour', 1.4 cm in diameter and 2.5 cm high. This was positioned in a 2.5 cm x 2.5 cm x 25 cm movable insert, which could move in the cranio-caudal direction with a range of 'breathing rates' and amplitudes. These could be set to variable values: between 9 and 24 breathing cycles per minute (bpm); and four amplitudes of 0.5, 0.9, 1.9 and 2.8 cm. Initially, point doses were measured in the centre of the tumour using a small volume CC04 ion chamber (IBA). The pilot use of this in a multi-centre intercomparison has been reported [6, 7], where a pre-set tolerance of 5% was used for moving target situations [8, 9].

The phantom has been further developed to also house radiochromic film for dose distribution intercomparisons. In this version, the moving insert has been increased in size to 6 cm x 6 cm x 25 cm, constructed from cedar (relative electron density ~ 0.3) and containing a cylindrical Solid Water ‘tumour’ oriented along the direction of motion, of 2 cm diameter and 2 cm length. The insert can be split to house and reproducibly position strips of EBT3 Gafchromic film of 5.5 cm width and 16 cm length (figure 2). The whole insert can be positioned in one of two orientations, so that film measurements can be performed in either sagittal or coronal planes. Films were read out on an Epson Expression 10000XL scanner, processed with a net OD method using locally written Matlab procedures (calibration curves, film positioning, conversion to dose on the red channel). Further analysis, including gamma analysis and dose convolution, was performed using RIT113 v6.2 and OmniPro ‘mRT v1.7 software.

It may be noted that the changes to the phantom to house a larger insert for film measurements necessitated a design change for ion chamber measurements. The original smaller ion chamber insert has now been replaced to fit the enlarged void designed for the film insert. The larger ion chamber insert now has a ‘tumour volume’ matching that in the film insert for consistency and is machined to house the CC04 chamber in the centre of that volume.

Figure 1. ‘Respiratory’ phantom in original ion chamber measurement mode, showing: overall appearance; phantom split to reveal internal construction; and schematic of the moving insert. In the central figure: (a) ‘Thorax’ (water-equivalent slabs); (b) ‘lungs’ (tissue-equivalent foam); (c) ‘Tumour’ (Solid Water™); (d) Motorized drive system, with variable speed selection and interchangeable eccentric ‘wheels’ to control amplitude; (e) Vertically moving platform added for Varian RPM™ system.
2.2 Pilot and feasibility measurements
The intention is to use the phantom and measurement systems to intercompare performance in different centres, having a wide range of approaches to 4D lung radiotherapy, and to carry out end-to-end testing to include imaging, delineation, planning and treatment dose delivery according to local 4D protocols. Detailed pilot and feasibility measurements were carried out initially in PoWH to thoroughly test the methods and procedures before such wider use. Thus the phantom underwent the current PoWH 3D and 4D imaging, planning and treatment delivery procedures for the static situation and for a range of combinations of motion amplitude and breathing rate (up to 12 scans, plans and deliveries to encompass up to 4 amplitudes and 3 breathing rates). Planning scans were obtained using a Toshiba Aquilion LB scanner, initially for exhale and inhale breath hold scans and also for a free-breathing scan and later using the Varian RPM system, fusing scans to delineate the ITV. Any ion chamber air cavities were over-written with surrounding ‘tissue’ density. Plans were created on the exhale phase (for comparison to static measurements) and also on average scans (for motion) with either CMS XiO 4.6 or Monaco 3.3, using 8 conformal beams to encompass the tumour motion. They were calculated for a fraction dose of 8 Gy for 6 and 10 MV beams on an Elekta Axesse linac. Plans were then delivered to the phantom using those beams and the measured doses (ion chamber) or distributions (film) were compared to planned values. Planned ‘point’ doses were calculated as a mean of relevant interest points placed in the plan along the range of tumour (chamber) movement. Dose deliveries were repeated three times per situation to test the reproducibility. For the film measurements, a more restricted set of conditions has been investigated (4 amplitudes, but for only one breathing rate of 14 bpm), but repeated three times for each film orientation. Gamma analysis was carried out using a 10% threshold, global normalization and analysis criteria of 3%/3mm and 5%/3mm, where the first tolerance criteria were selected to comply with general clinical practice tolerances and the second wider set to be consistent with the ion chamber intercomparison tolerance.

3. Results and Discussion

3.1 Ion chamber point dose measurements
Agreement between measured doses and mean planned doses in moving conditions at 14 bpm was observed to be within 1.4%, with a minor increase in the difference as motion amplitude increased. Specifically, average (and standard deviation) dose differences between measured and planned doses were observed of -0.32 (± 0.04)%, 0.44 (± 0.01) %, 0.83 (± 0.02)% and 1.40 (± 0.01)% for motion amplitudes of 0.5, 0.9, 1.9 and 2.8 cm respectively. Negative dose differences indicate that measured doses were less than planned and vice versa. In each case, the average and standard deviation values are from the three repeated measurements taken in each situation. The measurements were generally reproducible, as represented by the standard deviations. The influence of breathing rate was also assessed and in the range used (9-24 bpm) was found not to have any significant effect, ie within experimental uncertainty the dose differences were the same for a given motion amplitude, whatever the breathing rate. These results are for 3D conformal treatments and hence do not involve dynamic
deliveries; however the preliminary results from pilot studies involving IMRT and VMAT indicate that this finding is also supported for dynamic treatments, for this range of breathing rates [6,7].

3.2 Film measurements
Using repeated scans for the films from the static target case (no motion applied), the reproducibility of the scanner and the scanning methodology and process was high, with variations of no more than 0.5% in gamma evaluation pass rates. The preliminary results using Gafchromic film in the moving target phantom to measure dose distributions delivered in static mode agreed well with the planned values calculated on the exhale scan, with more than 95% of points passing a 3%/3mm gamma criteria and more than 99% of points passing a 5%/3mm gamma criteria. Under moving conditions, direct comparison of dose distributions calculated on the average scan and measured film values lead to gamma analysis results ranging from 98 to 32% of points passing the criteria from the smallest to the largest amplitudes for 3%/3mm (99 to 38% for 5%/3mm). The increasingly poorer agreement as motion amplitude increases is due to the average plans used not reflecting the whole effects of motion. The use of the ITV concept ensures that the GTV receives the expected dose, but the planned distribution is an average planned value whereas the measured distribution is a true smeared distribution as delivered. By convolving the dose distributions calculated according to the motion pattern, agreement better than 96% and 99% respectively were obtained, indicating that the methods are satisfactory, but that the region of interest for comparison needs further consideration.

4. Conclusion
The results indicate that the in-house respiratory phantom and associated methods can be used successfully to perform 4D commissioning and end-to-end QA, using different inserts to measure ion chamber point doses or film-measured dose distributions. Various issues observed in the feasibility studies, particularly for the film measurements, are being resolved by refinements of the method and analysis before beginning to use the system more widely for pilot multi-centre inter-comparisons over a range of scanners, TPSs, linacs, beam energies and modalities (FF and FFF) and delivery methods (3DCRT, IMRT, VMAT). These initial measurements are also being used to inform the decisions on tolerances for wider audit use. The phantom is versatile, modular and cost-effective for the intended purposes and besides being used for multi-centre intercomparisons has the potential also to be used for patient-specific validation of 4D hypo-fractionated lung treatment plans in a given centre.

5. References
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