Dosimetric evaluation near lung and soft tissue interface region during respiratory-gated and non-gated radiotherapy: A moving phantom study

W.L. Jong a, N.M. Ung a,⁎, Ath Vannyat a, b, A.B. Rosenfeld c, J.H.D. Wonde d,e
a Clinical Oncology Unit, Faculty of Medicine, University of Malaya, Kuala Lumpur, Malaysia
b Oncology Department, Calmette Hospital, Phnom Penh, Cambodia
c Department of Biomedical Imaging, Faculty of Medicine, University of Malaya, Kuala Lumpur, Malaysia
d University of Malaya Research Imaging Centre, Faculty of Medicine, University of Malaya, Kuala Lumpur, Malaysia

corresponding author at: Clinical Oncology Unit, Faculty of Medicine, University of Malaya, 50603 Kuala Lumpur, Malaysia.
E-mail address: nm_ung@um.edu.my (N.M. Ung).

Original paper

Abstract

Challenges in treating lung tumours are related to the respiratory-induced tumour motion and the accuracy of dose calculation in charged particle disequilibrium condition. The dosimetric characteristics near the interface of lung and Perspex media in a moving phantom during respiratory-gated and non-gated radiotherapy were investigated using Gafchromic EBT2 and the MOSkin detector. The MOSkin detectors showed good agreement with the EBT2 films during static and gated radiotherapy. In static radiotherapy, the penumbral widths were found to be 3.66 mm and 7.22 mm in Perspex and lung media, respectively. In non-gated (moving) radiotherapy with 40 mm respiratory amplitude, dose smearing effect was observed and the penumbral widths were increased to 28.81 mm and 26.40 mm, respectively. This has been reduced to 6.85 mm and 9.81 mm, respectively, in gated radiotherapy with 25% gating window. There were still some dose discrepancies as compared to static radiotherapy due to the residual motion. This should be taken into account in the margin generation for the target tumour.

© 2017 Associazione Italiana di Fisica Medica. Published by Elsevier Ltd. All rights reserved.

1. Introduction

Lung stereotactic body radiotherapy (SBRT) enables high radiation dose (~60 Gy) to be delivered hypo-fractionally to the target tumour while minimizing dose to surrounding healthy tissues [1]. Accuracy and precision are needed to ensure high tumour control probability along with low normal tissue complications. However, when treating lung tumours, there are issues with regard to tumour motion existing due to involuntary respiratory motion [2]. Previous studies found that tumour motion is greater along the cranio-caudal direction, with an average displacement of 12 mm [3,4]. The positional change of the lung tumour leads to dosimetric uncertainty such as dose smearing, dose blurring and deformation of the dose distribution that causes a detrimental effect in the therapeutic ratio [5].

When the displacement of the lung tumour is more than 5 mm, the AAPM Task Group 76 recommends the use of respiratory management techniques namely: motion-encompassing, breath-holding, forced-shallow-breathing, gating and tracking techniques [6–10]. In motion-encompassing technique, additional margin of clinical target volume (CTV) to planning target volume (PTV) is needed to ensure adequate dose coverage to the target tumour, similar to various systematic uncertainties chain in radiotherapy such as patient setup. However, this will potentially increase the probability of normal tissue complication because of larger normal tissue involvement.

By considering the respiratory motion and utilising gating technique or real time motion adaptive radiotherapy, the margin for intra-fractional tumour motion can be reduced. Real time motion adaptive radiotherapy utilizing image guidance and multileaf collimator (MLC) tracking for treating lung tumours have been proven to be attractive options to minimize CTV to PTV margins [11,12]. However, these methods are still not available in many radiotherapy facilities. Gating technique is an interrupting irradiation technique, where the radiation is delivered only during the pre-defined phase (gating windows) of the respiratory cycle. While respiratory gating technique is good for managing the tumour motion, some tumour motion (known as residual tumour motion) still occurs within the gating window [13]. The selection of the gating window’s width is a trade-off between residual tumour motion and treatment time [9,13–16]. Increasing the gating window’s width...
will increase the duty cycle (shorten the treatment time), but also result in greater residual tumour motion as a larger proportion of the total tumour motion will be captured [17]. The residual tumour motion may contribute to dosimetric error [18]. Thus, a margin is still needed.

Generally, the CTV to PTV margin is a geometrical concept that takes into consideration the geometrical variations such as tumour motion to ensure adequate dose coverage to the lung tumour. However, it is known that the lack of electronic equilibrium at the interface between the low density lung and the tumour causes an under-dosage at the periphery of the tumour [19]. The uncertainties due to dose calculation algorithms were not accounted in the margin generated to form PTV. It is clinically important to characterise dosimetric uncertainties due to respiratory motion near the interface of the lung and tumour.

Alhakeem et al. have investigated the interface dosimetry using several dosimetric techniques including a MOSFET-based detector, the MOSkin detector and Monte Carlo (MC) calculation that facilitates the use of BEAMnrc/DOSXYZnrc models [20]. They used the MOSkin detector to study the depth dose near the interface region of water and air, water and steel, and water and lung. They found that the MOSkin measurement is in good agreement with MC calculation, except at the interface with steep dose gradient due to the volume averaging effect of the MC calculation’s voxels [20]. They concluded that the detector such as the MOSkin detector with small sensitive volume and tissue-equivalent materials could provide accurate dose assessment near the interface region of two different media.

This study investigated the dosimetric characteristics near the lung and Perspex interface on a moving phantom, which simulated a moving tumour’s interface or lung and soft tissue interface. Specifically, the longitudinal dose profiles across the lung and soft tissue interface during respiratory-gated radiotherapy were experimentally assessed using radiochromic films and the MOSkin detectors. The possible margin reduction using respiratory-gated technique was investigated.

2. Materials and methods

2.1. Experimental setup

All measurements were carried out under 6 MV photon beam with 1000 MU/min using a Novalis Tx linear accelerator (Varian Medical System, Palo Alto, CA). This linear accelerator is equipped with Exactrac gating system (BrainLAB AG, Heimstetten, Germany). The Exactrac gating system used an illuminator to emit infrared toward the infrared reflective (IR) markers attached on the phantom or patient. Two cameras were used to track the motion of the reflective markers on the phantom [21].

An IMRT dose verification phantom (Standard Imaging, Middleton, WI) positioned on a respiratory gating platform (Standard Imaging, Middleton, WI) was used. The IMRT dose verification phantom consists of 3 Perspex slabs and 2 Perspex slabs with lung equivalent insert, with the thickness of 3 cm for each slab. The Perspex slabs with lung equivalent insert were sandwiched between one piece of Perspex slab on top with another two Perspex slabs at the bottom (Fig. 1). Since the respiratory motion is usually most pronounced in the cranial-caudal direction [3], the phantom was positioned and set to move in horizontal direction to mimic lung motion in the cranial-caudal direction (longitudinal direction). An in-house customised platform capable of moving in the vertical direction was designed and attached to the respiratory gating platform to mimic the respiratory-induced chest wall motion. The pattern of the respiratory movement can only follow a sine function and there was no offset between the vertical and horizontal motion. Five IR markers were positioned on the vertical platform as external surrogates for respiratory motion tracking. This phantom combination is henceforth called as “moving phantom”.

As the moving phantom possesses similar tissue heterogeneity to the lung and soft tissue, the dosimetric characteristics near the lung and Perspex (lung-Perspex) interface of the moving phantom were assessed. The lung-Perspex interface of the moving phantom at its home position (middle position between the peaks

**Fig. 1.** Perspex slabs IMRT dose verification phantom with lung equivalent insert was sandwiched within the Perspex slabs. The interface of the lung and Perspex media was irradiated with 6 MV photon beam with 4 × 3 cm² field size. The dots indicate the positions of the MOSkin detectors sandwiched in between two Perspex slabs with lung insert.
of the respiratory amplitude) was aligned to coincide with the radiating isocentre. The interface was exposed with a single direct beam perpendicularly. Three types of irradiations were simulated: phantom in non-moving state with continuous irradiation with 4 × 3 cm² photon beam, phantom in moving state with continuous irradiation and phantom in moving state with amplitude-based gated irradiation. For simplicity, these irradiations will be referred to as static radiotherapy, non-gated radiotherapy, and gated radiotherapy, respectively. Details of the respiratory operation’s parameters are shown in Table 1.

### 2.2. Gafchromic EBT2 films and the MOSkin detector

Selection of a suitable detector is very important to characterise the lung and soft tissue interface dosimetry. The size of the detector must be small, especially the sensitive volume, in order to provide high spatial resolution. In this work, Gafchromic EBT2 films (International Specialty Products, Wayne, NJ) and the MOSkin detectors were used to measure the dose near the lung and Perspex interface. The EBT2 films were cut into sizes of 40 (lateral) × 50 (longitudinal) mm² for dose profile measurement. All films were placed in landscape orientation at the centre of an Epson Expression 10000XL flatted scanner (Epson America, Long Beach, CA) to reduce film–scanner-induced change in pixel values. The films were scanned in RGB format with a resolution of 96 pixels per inch. A median filter of 5 pixels was applied. Only the red channel was used for analysis. Image analysis was performed using ImageJ version 1.43 U (National Institute of Health, Bethesda, MD). The overall uncertainty for EBT2 films for dose measurement in radiotherapy was 2.8% (1 SD) [22].

The MOSkin detector is a special design of p-MOSFET-based detector, developed at the Centre for Medical Radiation Physics, University of Wollongong, Australia. The silicon chip with dimension of 0.6 × 0.8 × 0.35 mm³ is “dropped-in” a Kapton pigtail strip and is sealed with a layer of thin polyamide films with water-equivalent thickness of 0.07 mm. Characterisation of the MOSkin detector has been reported [23–25]. The MOSkin detector is known for its capability for skin dose measurement [23,25,26]. It is also suitable for dose measurement in steep dose gradient region such as small radiation field [27] and near interface region [20] due to asymmetric structure of the detectors. A set of standard films were irradiated to establish a calibration curve (dose range from 0 to 1000 cGy) for EBT2 films while an average calibration factor of 2.323 ± 0.115 mV cGy⁻¹ was used for all MOSkin detectors.

Before evaluating the dosimetric characteristics near the interface region, the radiation output constancy of a linear accelerator in non-gated or gated operation has to be assessed. According to AAPM Task Group 142, the radiation output of a linear accelerator should be within ±2% during gated and non-gated (static) operation [28]. The output constancy of the linear accelerator was assessed using the farmer chamber at the depth of maximum dose in a solid water phantom and was found to be within ±2%.

The dosimetric comparison of gated and non-gated mode of a linear accelerator was performed. The lung inhomogeneity slabs of the moving phantom were replaced with Perspex slabs. Two hundred monitor units were delivered for all irradiation conditions. The radiation output at the isocentre was measured with the EBT2 films and the MOSkin detector at depth of 6 cm in the moving phantom. The average of the central 5 × 5 pixels area around the central axis of the films was taken and analysed. All measurements were repeated twice.

### 2.4. Dose profile measurement

The dose profiles at depth of 6 cm (between the Perspex slabs with lung insert) in the moving phantom along the longitudinal direction across the lung and Perspex interface were measured with the MOSkin detectors and EBT2 films. Nine MOSkin detectors were used and positioned along the central axis of the radiation beam with interval of 5 mm between the detectors, with one detector at the isocentre (Fig. 1). The positioning accuracy of the MOSkin detector was estimated to be within ±1 mm. All MOSkin measured dose profiles were normalised to the dose measured with the MOSkin detector at the central axis of the radiation beam while EBT2 dose profiles were normalised to the average of the central 5 × 5 pixels area around the central axis. This is to aid the identification of the desired isodose level for evaluation. The penumbral width (distance between 20% and 80% isodose) of the dose profiles for non-gated, gated and static radiotherapy were determined.

### 3. Results and discussion

#### 3.1. Output constancy

Fig. 2 shows the measured radiation output of the linear accelerator under static, gated and non-gated radiotherapy. All measured doses were normalised to 1 at the EBT2 films measured dose during static radiotherapy. In static radiotherapy, the measured doses at the isocentre of the radiation beam were 144.92 ± 1.58 eGy and 145.69 ± 1.96 eGy with EBT2 films and the MOSkin detector, respectively.

In non-gated radiotherapy, the radiation output measured with EBT2 films for 20 mm and 40 mm respiratory amplitudes were lower with deviation of −6.5% and −17.9%, respectively. No significant difference was observed for 10 mm respiratory amplitude. In

### Table 1

<table>
<thead>
<tr>
<th>Amplitudes</th>
<th>Gating windows (range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static radiotherapy</td>
<td>0 mm</td>
</tr>
<tr>
<td>Non-gated radiotherapy</td>
<td>10 mm, 20 mm, and 40 mm</td>
</tr>
<tr>
<td>Gated radiotherapy</td>
<td>10 mm, 20 mm, and 40 mm</td>
</tr>
</tbody>
</table>

$$RMSE = \sqrt{\frac{\sum (D - D_{EBT2})^2}{n}}$$

where RMSE is the root mean square error, $D$ is the MOSkin detector measured dose and $D_{EBT2}$ is the EBT2 films measured dose over the nine measurement points ($n$).
gated radiotherapy with 25% gating window, the radiation outputs corresponded well to static radiotherapy with the deviation of <2%. Deviations of 4.8% and 9.4% were observed for gated radiotherapy with gating window of 50% and 75%, respectively. This shows that the gated radiotherapy reduced the effect of respiratory motion on dose delivery accuracy during non-gated radiotherapy. However, larger gating window retains the residual motion, thus reducing the dose delivery accuracy.

Meanwhile, the agreement between the MOSkin and EBT2 films measurement for radiation output constancy was also evaluated (Fig. 2). Similarly, the MOSkin detector was found to be in good agreement with EBT2 films measurement during static radiotherapy and gated radiotherapy with different respiratory amplitudes, with the deviations of <2%, except for 40 mm respiratory amplitudes (>3%).

3.2. Dose profiles during static, non-gated radiotherapy and gated radiotherapy

Fig. 3 shows an example of the measured dose distribution using EBT2 films during static (no motion), non-gated and gated radiotherapy. In the case of non-gated radiotherapy, the moving phantom was set to move with motion amplitude of 40 mm. Comparing to static radiotherapy, there was a significant difference in the dose distribution. In non-gated radiotherapy, dose smearing effect was illustrated at the edge of the dose distribution along the moving direction, leading to the blurring of the high dose gradient region at the edge of the radiation field (penumbra region). Dose decrement was observed inside the radiation field while dose increment was observed outside the radiation field, resulting in under-dosage inside the target tumour while overdosing of the surrounding tissue. Fig. 4 demonstrates the measured dose profiles along the longitudinal direction during static, non-gated, and gated radiotherapy with different tumour motion amplitudes. Similar to Fig. 3, dose smearing effect was observed in non-gated radiotherapy and this dose smearing effect is more pronounced with the increase in the respiratory amplitude.

Unlike non-gated radiotherapy, the dose smearing effect has been reduced during gated radiotherapy with 25% gating window. The delivered dose distributions during gated radiotherapy and static radiotherapy are similar. However, there is still some dose discrepancies in the dose profiles due to the residual motion within the gating window during gated radiotherapy compared to static radiotherapy [18]. The residual tumour motion in the gating windows is dependent on the width of the gating window and the respiratory amplitude [8,14,18]. The residual motion is greater when the width of the gating window increases, resulting in more pronounced dose smearing effect as shown in Fig. 5. If the gating window is 100%, implying there is no gating, the residual tumour motion can be as large as in non-gated radiotherapy. Smaller gating window should be used in order to retain accurate dose distribution. However, this will prolong the treatment time. Falk et al. reported that the treatment time for amplitude-based gated SBRT is ~3.5 times longer than non-gated radiotherapy [18].

Fig. 2. Radiation output constancy during respiratory-gated radiotherapy using both MOSkin detector and EBT2 film. The error bars show 1 SD of three repeated measurements.

Fig. 3. Measured dose distribution using EBT2 films across the lung and Perspex interface during static radiotherapy (no motion), non-gated radiotherapy (motion amplitude of 40 mm) and gated radiotherapy with 25% gating window (motion amplitude of 40 mm). The vertical dot line indicates the measured dose profiles along the y-axis of the radiation field in each case.
Fig. 4. Dose profiles measured with EBT2 films and the MOSkin detectors during (a) static, non-gated and gated (25% gating window) radiotherapy with tumour motion amplitude of (b) 10 mm, (c) 20 mm, and (d) 40 mm. The vertical error bar shows 1 SD of three repeated measurements for each irradiation condition. The horizontal error bars represent the positioning error of 1 mm for the MOSkin detector.

Fig. 5. Dose profiles measured with EBT2 films during respiratory static, non-gated and gated radiotherapy with different gating windows.
The dose profiles were measured with the MOSkin detectors during respiratory-gated radiotherapy and compared against EBT2 films measured profiles as shown in Fig. 4. The MOSkin measured dose profiles corresponded well with the EBT2 films measurement during static radiotherapy and gated radiotherapy, with RMSE of <3%. The result is consistent with the reported result in previous studies where the MOSkin detector was used for dose measurement near the lung and water interface [20,29]. Alhakeem et al. found the difference between the MOSkin measurement was in agreement within ±3% with the MC simulation for depth dose measurement near lung and water interface [20].

3.3. Penumbral width

The penumbral width in both the Perspex and lung media was measured and summarised in Table 2. During static radiotherapy, steeper dose gradient (narrower penumbral width) appears in Perspex media than lung media as illustrated in Fig. 4. The asymmetrical dose profiles can be explained by the longer range of the lateral scattered electron in the low density media (lung), compared to water equivalent material (Perspex) [30–32]. This resulted in the lateral electronic disequilibrium occurring at a larger distance from the geometrical beam edge in lung compared to Perspex media. Therefore, a decrease in the sharpness of the dose profiles (wider penumbral width) was observed in lung media.

When the radiation was delivered in non-gated mode, dose smearing effect appeared. The penumbral widths of the dose profiles were wider in both lung and Perspex media than static radiotherapy. The dose smearing effect was found to be less pronounced in lung media compared to Perspex media with increasing tumour motion amplitudes. This is probably due to the fact that the respiratory amplitude (phantom motion) used in this study is relatively smaller than the range of the lateral scattered electron in lung media compared to Perspex media. This is assuming the range of scattered electron is equal to the CSDA (continuous slowing down approximation) range [33] of 6 MeV electron, which is 3.162 g cm⁻² and 3.088 g cm⁻², respectively in Perspex (density of 1.18 g cm⁻³) and lung (~0.3 g cm⁻³) media. The scattered electron may travel up to 2.68 cm laterally in Perspex media and 10.29 cm in lung media. This distance is assumed to be the starting point of lateral electronic disequilibrium from the geometrical edge of the radiation beam. In the case of 40 mm respiratory motion in this study (Fig. 4(d)), the range of the scattered electron in lung media is relatively greater than the motion, thus, the dose smearing effect is less to the penumbral of the dose profiles in lung media compared to Perspex media.

The penumbral widths during gated radiotherapy were significantly reduced. During non-gated radiotherapy with 10 mm tumour motion amplitude, the penumbral width was 9.13 mm and 11.52 mm in Perspex and lung media, respectively. The penumbral width was reduced to 4.26 mm and 7.92 mm during gated radiotherapy with 25% gating window, with an effective reduction of 53% and 31%, respectively.

For respiratory amplitude of 40 mm, the penumbral widths were reduced from 28.81 mm and 26.40 mm to 6.85 mm and 9.81 mm in Perspex and lung media, with effective reduction of 76% and 63%, respectively, during gated radiotherapy with 25% gating window. The effectiveness of respiratory-gated radiotherapy is more pronounced for larger tumour motion amplitude [34]. However, the effectiveness of the gated radiotherapy was decreased as the gating window increased. The residual motion within the gating window could result in dosimetric error such as blurring and deformation of the dose distribution and hence, degrade the actual dose distribution especially at the steep dose gradient region.

3.4. Margin for respiratory motion

As demonstrated in Fig. 3 and Fig. 4, the dose smearing effect due to the respiratory motion resulted in under-dosage inside the target tumour along with over-dosage to the surrounding normal tissue, especially with larger respiratory amplitudes. The under-dosage inside the target tumour should be taken into account in radiotherapy. As recommended by AAPM Task Group 76, the expected lung tumour motion has to be considered in the margin used for treatment planning [6].

It is interesting to understand the margin for respiratory-induced tumour motion needed for motion encompassing technique and also how much margin reduction is possible by using gated technique. According to Engelsman et al., the margin for intra-fractional respiratory motion is defined as the increase in margin of CTV to PTV necessary to ensure the same tumour coverage as without intra-fractional motion [35].

In this study, the margin for the intra-fractional respiratory motion (M<sub>resp</sub>) was determined by evaluating the agreement between 95% isodose levels of the EBT2 films measured dose profiles during non-gated or gated radiotherapy with static radiotherapy in terms of dose-to-distance agreement (DTA) [36,37]. The measured margin (M<sub>resp</sub>) was then compared against the calculated margin using van Herk’s margin recipe [38,39]. By accounting for the random uncertainties only, the notation that describes the additional margin for the intra-fractional respiratory motion (M<sub>resp</sub>) is:

\[
M_{\text{resp}} = M_{\text{non-gated/gated}} - M_{\text{static}}
\]  

(2)

\[
M = \alpha(\sigma - \sigma_p)
\]  

(3)

\[
\sigma = \sqrt{\sigma_{\text{motion}}^2 + \sigma_{\text{resp}}^2 + \sigma_p^2}
\]  

(4)

where \(M\) is the margin during static (\(M_{\text{static}}\)), non-gated (\(M_{\text{non-gated}}\)) or gated radiotherapy (\(M_{\text{gated}}\)), \(\alpha\) is a numerical value of 1.64, which corresponds to 95% isodose coverage of the tumour, and \(\sigma\) is the

Table 2

<table>
<thead>
<tr>
<th>Amplitude</th>
<th>Penumbra width, mm</th>
<th>Gating window</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Perspex</td>
<td>Lung</td>
</tr>
<tr>
<td>Static</td>
<td>3.66</td>
<td>7.22</td>
</tr>
<tr>
<td>10 mm</td>
<td>9.13</td>
<td>11.52</td>
</tr>
<tr>
<td>20 mm</td>
<td>16.53</td>
<td>17.37</td>
</tr>
<tr>
<td>40 mm</td>
<td>28.81</td>
<td>26.40</td>
</tr>
<tr>
<td>10 mm</td>
<td>28.81</td>
<td>26.40</td>
</tr>
<tr>
<td>40 mm</td>
<td>28.81</td>
<td>26.40</td>
</tr>
</tbody>
</table>

* Identical value for non-gated radiotherapy.
The \( \sigma_{\text{motion}} \) is assumed to be about 0.4 times the amplitude of respiratory motion, which can be assumed to have a Gaussian probability density function \([35]\). For \( \sigma_{\text{motion}} > 5 \text{ mm} \), a correction factor as suggested by Engelsman et al. was applied \([35]\). Since the proportion of the movement of the moving phantom in lung and Perspex media is equal, the respiratory amplitude will be equalled to half of the total respiratory amplitude. The \( \sigma_{\text{setup}} \) is assumed to be 3 mm, which is the typical patient setup error \([4]\). The \( \sigma_{W} \) was obtained based on the penumbral width of the dose profiles during static radiotherapy, which was 7.22 mm and 3.66 mm in Perspex and lung media, respectively. For gated radiotherapy, the respiratory motion of the moving phantom is uniform. The \( \sigma_{\text{setup}} \) of the residual tumour motion was determined since it is known and corresponded to the width of the gating windows.

Table 3 shows the additional margin (\( M_{\text{resp}} \)) for the respiratory motion determined using films measurement (using DTA) and van Herk's margin recipe. Considering a delay of 1.05 mm of the gating system and the radiation beam trigger was found in our previous work \([40]\), the measured margins are in good agreement (within 1 mm difference) with the calculated margins using van Herk's margin recipe, for both non-gated and gated radiotherapy. In non-gated radiotherapy, larger \( M_{\text{resp}} \) is required and increases with the respiratory amplitude.

Compared to non-gated radiotherapy, the measured and calculated margins were much smaller for gated radiotherapy. This shows that the margin reduction was attainable for gated radiotherapy and the dose smearing effect has been reduced. However, a small margin is still needed for the residual motion and this residual motion increases with the gating window. For example, using 50% gating window for 40 mm respiratory amplitude requires margins of 4.07 mm and 2.48 mm in Perspex and lung media, respectively. The margins increased to 7.02 mm and 4.64 mm for 75% gating window. The true value of gated radiotherapy can only be retained with a smaller gating window at the expense of prolonging the treatment time.

4. Conclusion

This study has explicitly investigated the dosimetric characteristics near interface region in a moving phantom during non-gated and gated radiotherapy. Dose smearing effect was observed during non-gated radiotherapy and was more pronounced with larger respiratory amplitude. This effect can be reduced with gated radiotherapy, but it cannot be fully eliminated due to the residual motion within the gating windows. The residual margin is greater in larger gating window.

The dose smearing effect due to the respiratory motion which resulted in under-dosage inside the target tumour should be taken into account in radiotherapy, either by increasing the margin (motion encompassing technique) or using respiratory tracking system to gate the beam to the moving target (gating technique). In motion encompassing technique for respiratory motion of 40 mm, margins of at least 10.80 mm and 8.02 mm in Perspex and lung media, respectively, are needed to ensure full dose coverage to the target tumour with 95% isodose level. The margins can be furthered reduced to 1.80 mm and 0.44 mm in Perspex and lung media, respectively, by using 25% gating window during gated radiotherapy. A small margin is still needed to compensate for the residual motion.

The MOSkin detector has small sensitive volume, water-equivalent packaging, and minimal perturbation effect. It is suitable for dose assessment near the interface region of two different media. This has been shown in the good agreement that was seen between the MOSkin detectors and the EBT2 films in the dose profile measurement during static and gated radiotherapy.

Acknowledgments

The authors would like to thank all the radiographers and medical physicists in the Clinical Oncology Unit of University of Malaya Medical Centre for their assistance in this work. This study was supported by the University of Malaya Postgraduate Research Fund PPP (Grant number PG202-2015B).

Conflicts of interest

The authors have no relevant conflicts of interest to disclose.

References
