Technical Note

Original paper

Dosimetric analysis of rib interference of the CTV during interstitial brachytherapy of lung tumors

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Abstract

Purpose: In interstitial brachytherapy for lung tumors, the placement and alignment of the source needles are influenced by the ribs, which can affect the dose distribution. This study evaluated the change in dose to the target by comparing the dose between the actual interstitial brachytherapy plan (AIBP, what is deliverable due to anatomic constraints), and the virtual interstitial brachytherapy plan (VIBP, pretreatment-modified dose distribution).

Material and methods: AIBPs and VIBPs were designed for 20 lung tumors. The VIBP was designed with uniform spacing between needles, regardless of the presence of ribs. The prescription dose was 30 Gy. The percentage of normal ipsilateral lung volume that received a dose ≥ 5 Gy (V_5), conformity index (COIN), incremental dose percentage (IDP) to the target, and the dose covering 95% (D_{95}) of the clinical target volume (CTV) were calculated.

Results: The V_5 of the VIBPs was significantly smaller than that of the AIBPs ($p < 0.01$). The mean COIN value was 0.41 ± 0.12 for the AIBPs, which was significantly smaller than the value 0.54 ± 0.12 for the VIBPs ($p < 0.01$). The D_{95} of CTV in VIBP-adjusted was greater than that in AIBPs ($p < 0.01$). The mean IDP was 44% ± 40%. The D_{max} of the ribs was 20.16 Gy ± 15.76 Gy in AIBPs, and 18.57 Gy ± 15.14 Gy in VIBPs, which was not significantly different ($p > 0.05$).

Conclusions: The regular geometric alignment of needles is important for increasing the target dose and limiting the normal lung dose in interstitial brachytherapy for thoracic tumors. Thus, we recommend that radiation oncologists attempt to achieve the regular alignment of needles during implantation.

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Key words: interstitial brachytherapy, CTV dose, lung cancer, ribs dose.

Purpose

A fundamental principle of radiotherapy is to maximize the dose to the target, while minimizing the dose to normal tissues [1]. For thoracic tumors, to avoid missing the target due to respiratory motion, a margin of error is added to the region of interest during external beam radiotherapy, which often increases the dose to normal lung tissue. In order to solve this problem, researchers have explored internal irradiation techniques, such as computed tomography (CT)-guided percutaneous high-dose-rate interstitial brachytherapy (PIBT). This method utilizes needles implanted into the tumor to deliver radiation, thereby minimizing the effects of respiratory motion at the tumor site. To create a homogeneous and conformal target dose, it is common practice to implant multiple needles at equal intervals, parallel to one another, or one needle passing though the center of the clinical target volume (CTV) [2,3,4,5]. However, if the tumor is in the lung and surrounded by ribs, it is difficult to achieve uniform needle placement [6], as intercostal spaces are very small and variable (ranging from 5-20 mm) [7], requiring the use of CT guidance for needle placement. In addition, the motion of the ribs and intercostal spaces due to respiration interferes with ideal needle placement. As a result, needle alignment can be irregular, which results in a decline of the conformity index (COIN) and an increase in the normal lung dose. This study analyzed and estimated the influence of rib interference on the dose to the target area.

Material and methods

Patient characteristics

Twenty patients with lung tumors who underwent PIBT with a ^{192}Ir high-dose-rate afterloder (microSelectron-HDR, Elekta, The Netherlands) were included in this analysis (Table 1). All needles were implanted in the interspace of the ribs under CT guidance (0.5 mm slice thickness, 120 kV, 200 mA). In fifteen cases, more than two needles were implanted in an irregular arrangement

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(Figure 1A). The median number of needles implanted was 3 (range, 2-5) (Figure 1A). In the remaining five patients, one needle was implanted that did not pass through the center of the CTV having a diameter < 3 cm (Figure 1B).

The surgical team included a senior radiation oncologist, nurses, a medical physicist, and CT technicians. The radiation oncologist had experience with transthoracic needle aspiration biopsies and was responsible for the insertion of needles during the procedure. The nurses assisted the radiation oncologist and monitored the vital signs of the patient. The medical physicist provided information of the position, direction, and depth of the needle to the radiation oncologist for reference.

After the needles were placed, a CT scan of the whole lung was acquired and transferred to the three-dimensional (3D) radiotherapy planning system (TPS) (Oncentra 4.3, Elekta, Sweden). Treatment plans were created using a collapsed cone convolution dose calculation, and the calculation grid size was 0.3 cm. Contours of the CTV, ribs, and lungs were manually outlined on serial CT images by a senior radiologist.

Actual interstitial brachytherapy plan and virtual interstitial brachytherapy plan

Two plans were included for review for each patient: the actual interstitial brachytherapy plan (AIBP) and a virtual interstitial brachytherapy plan (VIBP). The AIBP was defined as the actual brachytherapy plan that was implemented by the afterloading unit. The placement of needles in each AIBP was limited by the ribs, resulting in needles that were not always parallel with equal intervals or one needle implanted off-centered inside the CTV (Figure 1).

Table 1. Patient characteristics

Characteristics	Median *n* (range)
Total No. of patients (*n*)	20
Gender	
Males	12
Females	8
Age (y)	58 (45-70)
Location (*n*)	
Left lung	13
Right lung	7
CTV (cm^3)	42.87 (6.90-1179.63)
Lungs (cm^3)	2615.21 (2312.38-3018.67)
Ipsilateral lung (cm^3)	1159.31 (1055.00-1571.29)
Ribs (cm^3)	21.95 (11.54-34.91)

Using the AIBP as a template, an additional plan (VIBP) was designed for each patient with ideal needle placement in a virtual manner. Virtual needles were allowed to pass through the ribs to achieve uniform arrangement in the tumor with 1 cm spacing between needles (Figure 2A) or one virtual central needle passing through the CTV center (Figure 2B). For both the AIBP and VIBP, the dwell step size was 0.25-0.75 cm. In accordance with a recent report on interstitial brachytherapy for lung tumors, a single dose of 30 Gy was adopted as the prescription dose (PD) [8]. In the TPS, both plans were optimized using a graphics optimization tool. Plans were acceptable after meeting the following constraints:

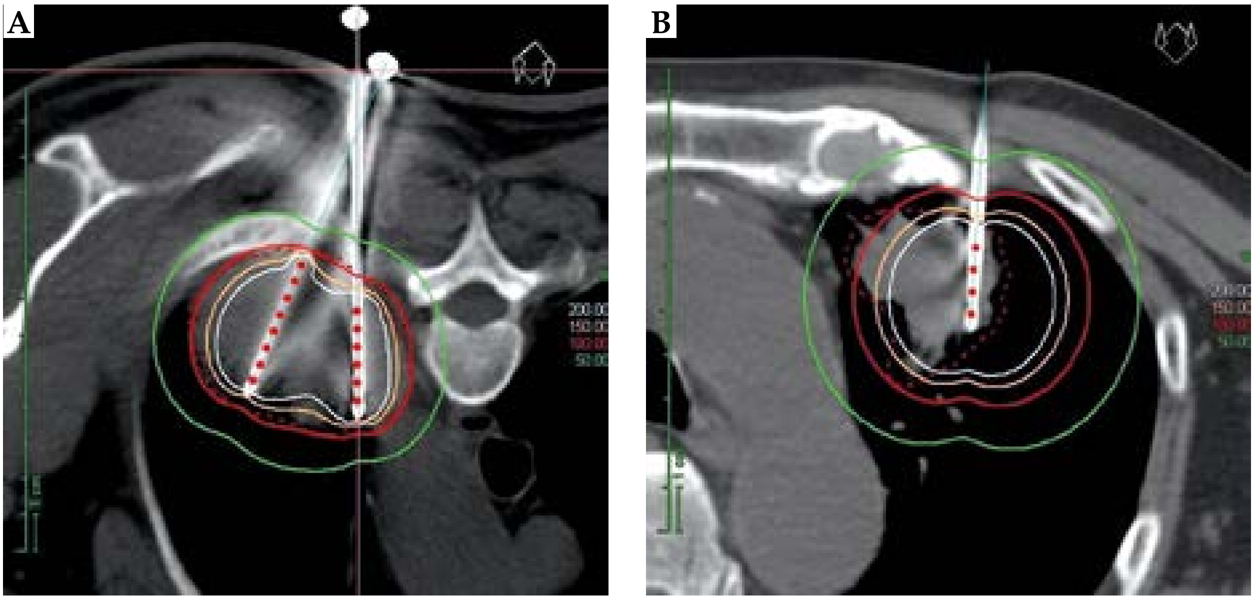

Fig. 1. Computed tomography images of needle positions due to rib interference during implant. Red dots are dwell positions, red dotted line is the clinical target volume (CTV) contour, solid lines are isodose curves, green solid line is 50% of the prescription dose, red solid line is 100%, yellow solid line is 150%, and white solid line is 200%. **A)** Two needles that were not parallel were implanted by passing through one available gap. **B)** single needle implant off-centered inside the CTV

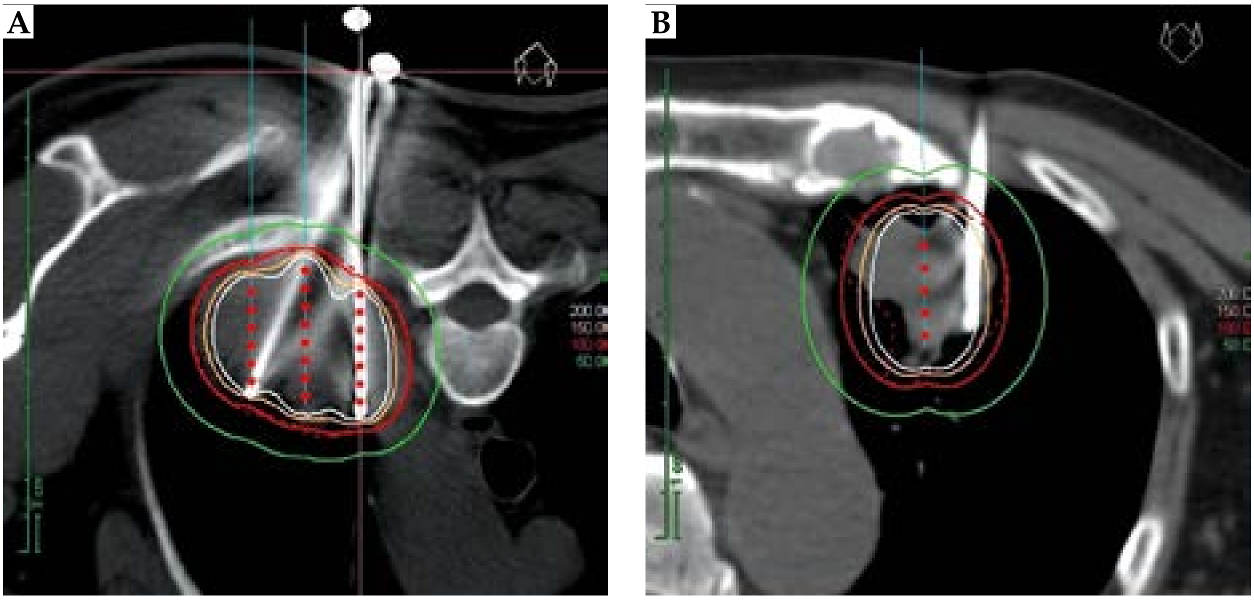

Fig. 2. Example of the regular arrangement of interpolation needles in virtual interstitial brachytherapy plan. **A)** Virtual needles were allowed to pass through the ribs to achieve uniform arrangement in the tumor with 1 cm spacing between needles. **B)** One virtual central needle passing through the clinical target volume center

95% coverage of the CTV by at least 100% of the PD ($D_{95} \geq$ PD), and the percentage of normal ipsilateral lung volume that received a dose ≥ 5 Gy (V_5) was minimized. In most cases, a $V_5 < 65\%$ for the ipsilateral lung was achievable. However, when the CTV was large, it was difficult to meet this constraint. The V_5 parameter is used in our institution to guide plan acceptance, in hope of reducing side effects like radiation pneumonitis [9], but note that there are no standard reference criteria for dose limits for this type of brachytherapy, and we referred to the work of Xiang *et al*. [8].

Adjusted VIBP

To determine how much the dose to the target could be reduced by interference of ribs, we first adjusted the ipsilateral lung V_5 value in the VIBP using a graphical global optimization tool in the TPS. The 100% isodose line was enlarged in TPS to achieve an equal value as the ipsilateral lung V_5 value in the AIBP. This revised VIBP was renamed VIBP-adjusted. The ΔD_{95} of the CTV was defined as the difference in D_{95} of the CTV between the VIBP-adjusted and the AIBP: $\Delta D_{95} = D_{95\ \text{VIBP-adjusted}} - D_{95\ \text{AIBP}}$. The incremental dose percentage (IDP) was defined as the ΔD_{95} divided by D_{95} of the CTV in the AIBP: $\text{IDP} = (\Delta D_{95}/D_{95\ \text{AIBP}}) \times 100\%$. The ΔV_5 was defined as the difference of the ipsilateral lung V_5 between the VIBP and the AIBP: $\Delta V_5 = V_{5\ \text{AIBP}} - V_{5\ \text{VIBP}}$.

Table 2. Dose parameters of D_{95} (PD = 30 Gy)

Plans	D_{95} (Avg ± st. dev) Gy	*p*
VIBP	30.09 ± 0.14	0.81
AIBP	30.09 ± 0.23	< 0.01
VIBP-adjusted	45.01 ± 14.02	

PD – prescription dose, VIBP – virtual interstitial brachytherapy plan, AIPB – actual interstitial brachytherapy plan, D_x – minimum dosage received by 95% of CTV, St. dev – standard deviation

Conformity index

The conformity index (COIN) was calculated as COIN = coverage factor (CF) × spill factor (SF), and described how well the reference dose encompassed the target volume and excluded non-target structures [10]. This value is always less than or equal to 1, and a COIN value closer to 1 indicates a more conformal plan. The CF was defined as the percentage of CTV volume receiving at least 30 Gy. The SF was defined as the percentage of CTV receiving 30 Gy relative to total 30 Gy volume.

Statistical analysis

The relationship between IDP and V_5 was evaluated using linear regression analysis, correlation is significant at the 0.05 level. The differences in D_{95}, COIN, the max dose (D_{max}) of the ribs, and V_5 were tested for statistical significance using a non-parametric Wilcoxon test with SPSS version 19.0 software. A *p* value less than 0.05 were considered statistically significant.

Results

There was no significant difference in the D_{95} of the CTV ($p > 0.05$) between the AIBPs and VIBPs. We did observe a significant improvement in D_{95} with the VIBP-adjusted plans compared to the AIBP plans (Table 2). The mean COIN was 0.41 ± 0.12 in the AIBPs, and 0.54 ± 0.12 in the VIBPs, which was a significant difference ($p < 0.01$).

The D_{max} of ribs was 20.16 Gy ± 15.76 Gy in the AIBPs, and 18.57 Gy ± 15.14 Gy in the VIBPs, which was not significantly different ($p > 0.05$). Dose parameters of V_5 for the ipsilateral lung are shown in Table 3. The mean IDP was 44% ± 40%. The IDP decreased by at least 15% with the ΔV_5 in the ipsilateral lung increased by 1%, as shown in Figure 3.

Table 3. Dose parameters of V_5 for the ipsilateral lung

Plans	V_5 ([Avg ± st. dev]%)	*p*
VIBP	21.31 ± 16.67	< 0.01
AIBP	28.69 ± 18.81	0.17
VIBP-adjusted	28.73 ±18.88	

V_5 – percentage of lung volume received 5 Gy, VIBP-adjusted – revised VIBP achieved an equal value as the ipsilateral lung V5 value in AIBP

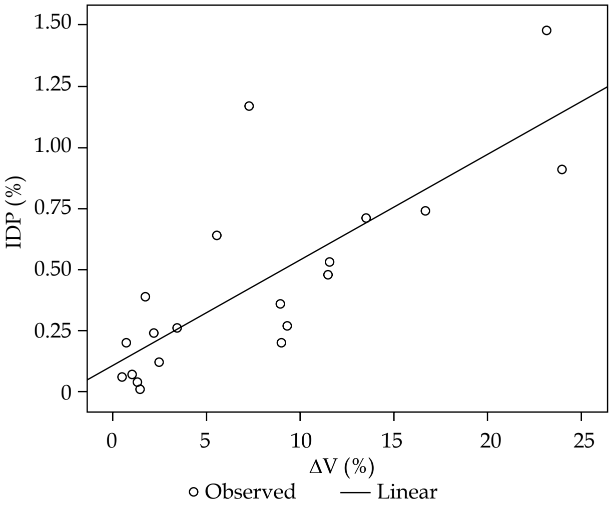

Fig. 3. Regression curve of the ΔV_5 and incremental dose percentage ($y = 0.043x + 0.109$, $R^2 = 0.62$; $p < 0.05$)

Discussion

Although several treatment options exist for the treatment of lung tumors with radiation, interstitial brachytherapy offers some advantage when considering tumor motion. Some radiologists [11,12] have pursued interstitial brachytherapy for managing tumor motion due to respiration during treatment [13,14], and with the help of 3D treatment planning software, it has become simple and practical to deliver highly conformal dose distributions to the target with brachytherapy [15].

In the clinical setting, the arrangement of implanted needles is an important factor for planning. However, due to rib interference, there are 3 main arrangement for needles: 1) multiple needles aligned with intersections inside the CTV (Figure 1A); 2) single needle off-centered inside the CTV (Figure 1B); 3) multiple parallel needles within in the CTV (Figure 4). For the plans with irregular arrangements of needles (1 and 2, above), there was a decrease in the COIN and an increase in the lung dose compared to the VIBP plans. It should be noted that the arrangement described as 3) was not included in our dosimetric comparison study. Although the arrangement of needles in 3) is in accordance with clinical practice rules, this pattern is often achieved only with a longer puncture distance due to rib interference, which could lead to additional lung injury. A long puncture distance with a parallel needle arrangement is only used as a last option for an implant at our institution.

During plan optimization, the dose to the normal lung was typically the limiting factor in increasing the dose to the target [16]. If an equal probability of side effects exists with a certain lung dose, decreasing the dose to the target area may result in an increased risk of recurrence or a decrease in the local control rate. It is expected that an irregular arrangement of needles could lead to a decrease in the dose to the CTV. However, our results also showed that the mean IDP to CTV could be increased by 44%, and PD dose could be reduced by about 15%, with the V_5 of the ipsilateral lung increased by 1% with irregular arrangement. Thus, attempting to achieve regular alignment of needle during implant is a pressing concern for thoracic tumors.

The implantation of needles by hand was affected by two factors: ribs and respiratory movement. The combined effect of these two factors results in alignments that are not parallel as not all rib gaps can provide a pathway for insertion. Unfortunately, we did not have access to real-time CT images of respiration, so it was difficult to account for respiration during needle placement (most prevalent in Type 2). According to our classification, Type 2 implant may also occur if the tumor is small and the respiration motion causes it to slip off the needle. Type 3 implants were difficult to achieve by hand in our study, but they represent the closest dose distribution to that of VIBP. If a special needle insertion device was available for implant from the anterior direction, a regular parallel arrangement of needles such as Type 3 could be achieved more frequently.

It is known that the arrangement of needles influences dose distribution. The optimizer of the treatment plan-

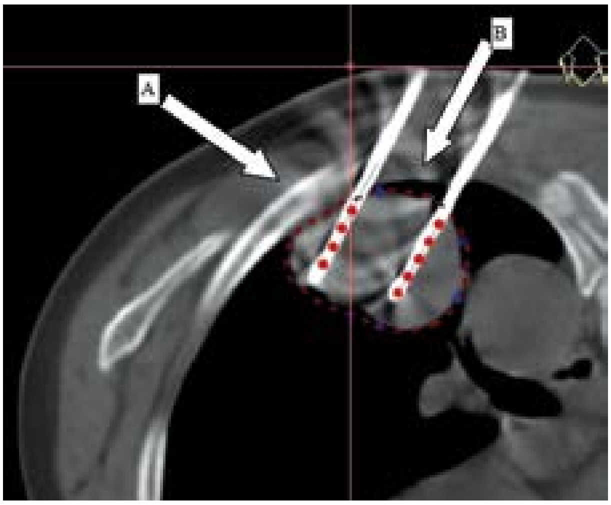

Fig. 4. Two needles were implanted into the tumor along "B" route. The "A" route, however, offered less damage to the lung, but was blocked by the ribs. The resultant dose distribution was closest to a virtual interstitial brachytherapy plan with needles in a parallel arrangement, which was not easy to achieve by hand

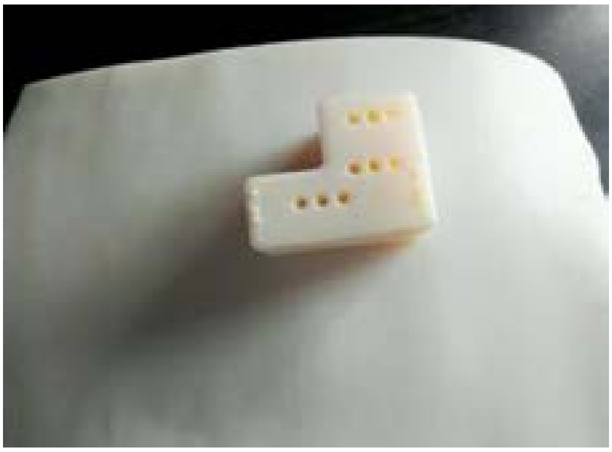

Fig. 5. 3D printed mold with preset needle pinholes. The mold has fixed channels for the needles and was 2 cm thick

Fig. 6. 3D template technology commonly used for ^{125}I seed implants [21]

ning system can improve the target dose and decrease the dose to normal tissue by adjusting dwell times, but cannot completely offset influences of the needle positions. During the implantation process, it is difficult to keep the needle direction fixed by hand. Shifts in the needle path may cause a deviation from planned position or a geometric miss of CTV. In order to solve this problem, we attempted to create a 3D-printed mold with a set of parallel pinholes with 2 cm in length to guide regular placement of needles for insertion (Figure 5). Unfortunately, this was unsuccessful due to respiratory motion and patient setup difficulties causing some of the pinholes to become useless during actual implant process. In the future, we hope to adopt the 3D template technology commonly used for ^{125}I seed implants [17,18,19,20]. As seen in Figure 6 [21], a regular parallel arrangement of needles has been achieved using a template for ^{125}I implants [21]. Perhaps with the help of a bone drill, a uniform arrangement with 1 cm spacing between needles (Figure 2A) or one central needle passing through CTV center (Figure 2B) could be possible for iridium-based PIBT. Additional investigation is needed as there are differences between ^{125}I and ^{192}Ir based techniques, such as the needle sizes, and the hypothesized use of 3D template and bone drill combination for ^{192}Ir treatments.

One of limitations in our study was small sample size. Future studies with a larger sample size may yield more accurate results. Nevertheless, we demonstrated the effect of rib interference on the target dose, and that arrangement of needles should be considered seriously by brachytherapy team.

Conclusions

The regular geometric alignment of needles is a key factor to increasing the target dose and limiting the lung dose in interstitial brachytherapy for lung tumors. The regular alignment of needles is mainly affected by rib interference. In order to obtain dose distributions close to VIBP distribution, additional implant techniques need to be explored to overcome the geometric restriction from ribs and respiratory movement.

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Disclosure

Authors report no conflict of interest.

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