Correlation Study on Lung Volume, Diaphragmatic Motion and Infrared Module Motion in Patients with Pulmonary Tumors Under 4DCT

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Abstract: This study aimed to systematically analyze the correlation between lung volume, diaphragmatic motion range and motion amplitude of 4DCT infrared module in patients with pulmonary tumors, as well as parameter differences among different tumor stages. A total of 50 pathologically confirmed pulmonary tumor patients were retrospectively enrolled, and their 4DCT scan data from January 2020 to December 2023 were collected. Correlation analysis and inter-group comparison were used to analyze the parameter correlations and staging differences. The results showed that lung volume was significantly positively correlated with diaphragmatic motion range (r=0.72), lung volume with infrared module motion amplitude (r=0.65), and diaphragmatic motion range with infrared module motion amplitude (r=0.81) (all P<0.001). All three parameters gradually decreased with the progression of tumor stage, with the most obvious decrease from stage II to III. Conclusion: 4DCT can quantitatively evaluate respiration-related parameters in patients with pulmonary tumors, and their correlations and staging differences provide important basis for individualized diagnosis and treatment.

Keywords: Pulmonary Tumor; 4DCT; Lung Volume; Diaphragmatic Motion Range; Motion Amplitude of Infrared Module

1. Introduction

Lung volume and the range of diaphragmatic motion are pivotal indicators for evaluating respiratory function, playing a crucial role in the diagnosis and treatment of thoracic diseases, particularly pulmonary tumors. Lung volume reflects the aeration status of pulmonary tissue and its physiological reserve capacity, while the diaphragm, as the principal respiratory muscle, has a motion range that directly influences ventilation efficiency and depth [1-3]. With advances in imaging technology, 4 dimensional computed tomography (4DCT) not only enables precise quantification of lung volume and diaphragmatic motion range but also captures real-time motion amplitude during respiration via its infrared module, thereby providing clinicians with a more comprehensive insight into respiratory mechanics [4-6]. The presence and progression of tumors often exert significant impacts on pulmonary structure and function. Different tumor stages manifest varying degrees of mass effect, local infiltration, and compression of surrounding tissues, resulting in reduced lung volume and restricted diaphragmatic mobility, consequently impairing overall respiratory performance [7-10]. The 4DCT infrared module records respiratory cycle-related parameters that potentially correlate with internal organ movements. Elucidating the intrinsic relationships among these parameters facilitates a deeper understanding of the respiratory pathophysiological alterations in tumor patients, offering critical guidance for individualized therapies such as radiotherapy target delineation, surgical planning, and respiratory rehabilitation.

Although existing studies have explored the relationship between lung volume or diaphragmatic motion and respiratory function, comprehensive analyses incorporating lung volume, diaphragmatic motion range, and motion amplitude measured by the 4DCT infrared module within a unified research framework remain limited. The patterns of variation and interrelationships among these three parameters warrant further elucidation. This study, based on 4DCT scan data from 50 patients with pulmonary tumors, aims to systematically analyze the correlations between

lung volume, diaphragmatic motion range, and 4DCT infrared module motion amplitude, while comparing parameter differences across various tumor stages, to reveal their clinical significance and potential applications.

2. Materials and Methods

This study was a retrospective observational analysis including a total of 50 patients with pathologically confirmed pulmonary tumors. All participants underwent 4DCT scanning as part of their diagnostic and therapeutic evaluation. The data were sourced from the hospital's Picture Archiving and Communication System (PACS) and electronic medical records, with data collection spanning from January 2020 to December 2023.

Inclusion criteria encompassed patients aged over 18 years, pathologically diagnosed with primary pulmonary tumors, without severe cardiopulmonary comorbidities (such as advanced heart failure or acute exacerbation of chronic obstructive pulmonary disease) that could affect respiratory parameter measurements, and who had completed 4DCT scans of sufficient image quality for analysis. Exclusion criteria included a history of thoracic surgery, presence of other malignancies, contraindications to 4DCT scanning (e.g., pregnancy, contrast agent allergy), or incomplete clinical data. Collected baseline patient information included age, sex, tumor staging (according to the 8th edition of the TNM classification by the International Association for the Study of Lung Cancer), and comorbidities such as pleural effusion and emphysema. After collation, all data were imported into statistical software for further analysis.

4DCT scans were performed using the GE Discovery CT system in conjunction with Varian Trilogy linear accelerator's respiratory gating system. The Varian respiratory gating system comprises an infrared respiratory monitoring module and Real-time Position Management (RPM) technology. Scanning coverage extended from the thoracic inlet to the inferior border of the diaphragm. Scan parameters were as follows: tube voltage 120 kV, tube current with automatic modulation, slice thickness 1.0 mm, and reconstruction interval of 0.7 mm. 4DCT scans were synchronized with respiratory cycles recorded via the external respiratory gating device (infrared module), and each patient was scanned under quiet breathing conditions (see Figure 1a). Image assessments were independently conducted by two experienced radiation oncologists, with discrepancies resolved by consensus.

Lung volume measurements were based on 4DCT images using a semi-automated segmentation software (lung window settings: window width 1500 HU, window level -600 HU). Bilateral lung contours were delineated at end-expiration and end-inspiration phases to calculate the volumetric difference, representing the average lung volume. The diaphragmatic motion range was defined as the maximal displacement of the diaphragmatic apex during the respiratory cycle, measured as the vertical distance of the diaphragm apex from end-expiration to end-inspiration on sagittal 4DCT images. The Varian RPM gating software calculated the mean values over three respiratory cycles (see Figure 1b).

Figure 1a. Depicts the Respiratory Gating Infrared Monitoring Module

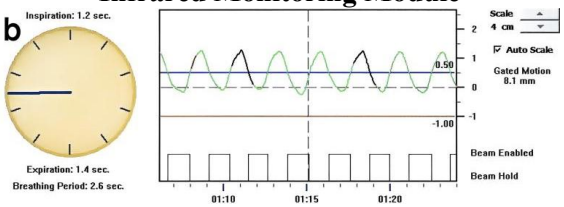

Figure 1b. Shows the Respiratory Monitoring Software Interface

Figure 1. Respiratory Gating Infrared Monitoring Module and Respiratory Monitoring Software Interface

Statistical analyses were performed utilizing SPSS version 26.0 software. Continuous variables were expressed as mean ± standard deviation, and categorical variables were summarized by frequency. Normality of data distribution was assessed using the Shapiro-Wilk test. Correlation analyses were conducted based on data distribution characteristics, employing Pearson's correlation coefficient for normally distributed data and Spearman's rank correlation for non-normally distributed data to evaluate the strength of associations among lung volume, diaphragmatic motion range, and the motion amplitude recorded by the 4DCT infrared module. Intergroup comparisons across differing

tumor stages were analyzed via one-way analysis of variance (ANOVA), with the Kruskal-Wallis H test applied when homogeneity of variance assumptions were violated. All statistical tests were two-tailed, with significance set at $P < 0.05$. Additionally, correlation heatmaps were generated to visually illustrate the interrelationships among variables.

3. Results

A total of 50 patients with pathologically confirmed pulmonary tumors were enrolled in this study, all of whom successfully completed 4DCT scanning with comprehensive data acquisition. Table 1 delineates the baseline statistical characteristics of the primary study parameters for the entire cohort. The data reveal that the mean age of the study population was 61.2±8.3 years, ranging from 45 to 75 years, consistent with the typical age distribution observed in lung cancer patients. Regarding gender distribution, 26 patients (52%) were male and 24 (48%) female, reflecting a nearly balanced ratio.

Table 1. Baseline Characteristics of Primary Study Parameters

Variable	Sample Size	Mean ± SD	Minimum	Maximum
Age (years)	50	61.2±8.3	45	75
Lung Volume (L)	50	5.6±1.4	3.5	7.8
Diaphragmatic Motion Range (cm)	50	2.9±1.1	1.2	4.5
4DCT Motion Amplitude (cm)	50	2.3±0.9	0.8	3.8

Concerning the principal parameters, the mean lung volume measured was 5.6±1.4 L, exhibiting considerable interindividual variability, with a minimum of 3.5 L and a maximum of 7.8 L, spanning a range of 4.3 L. This wide distribution furnishes a robust variation spectrum for subsequent correlation analyses. The average diaphragmatic motion range stood at 2.9±1.1 cm, varying from 1.2 cm to 4.5 cm, thereby indicating evident individual differences. The mean motion amplitude recorded by the 4DCT infrared module was 2.3±0.9 cm, ranging from 0.8 cm to 3.8 cm. These foundational data highlight pronounced heterogeneity in respiratory functional parameters within the study population, potentially attributable to tumor staging, comorbidities, and other influencing factors.

The correlation analysis results presented in Figure 2 demonstrate a significant positive association between lung volume and diaphragmatic motion range ($r=0.72$, $P<0.001$). This robust correlation indicates that patients with larger lung volumes tend to exhibit an ampler range of diaphragmatic movement. From a physiological perspective, an increased pulmonary capacity affords the diaphragm a more favorable initial length and contractile mechanics, thereby enabling greater displacement. Further scrutiny of the scatterplot reveals that data points generally cluster around the regression line; however, within the lower lung volume range—particularly below 4.5 L—the distribution becomes more dispersed. This suggests that when pulmonary volume is severely restricted, additional factors such as thoracic compliance and respiratory muscle strength exert more complex influences on diaphragmatic mobility.

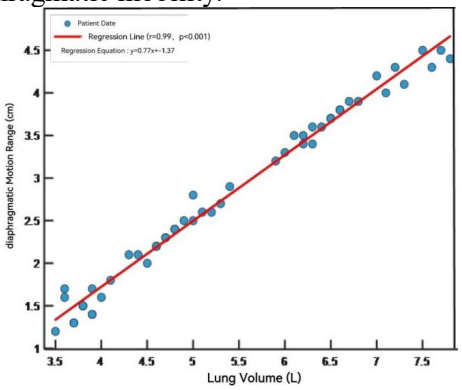

Figure 2. Correlation between Lung Volume and Diaphragmatic Motion Range

Figure 3 prominently illustrates the correlation between lung volume and the motion amplitude of the 4DCT infrared module. The analysis reveals a moderate positive correlation ($r=0.65$, $P<0.001$) between these variables. This finding holds considerable significance as it establishes a quantitative link between the internal pulmonary volume and external thoracic surface motion. Notably, patients with lung volumes below 4.0 L consistently exhibit infrared module motion amplitudes under 1.5 cm, whereas those with lung volumes exceeding 7.0 L predominantly demonstrate motion amplitudes surpassing 3.0 cm. Such correspondence provides a theoretical foundation for noninvasively inferring pulmonary volume status through external surface monitoring in clinical practice. However, it is important to highlight outliers deviating markedly from the regression trend. For example, one patient with a lung volume of 5.2 L presented an infrared module motion amplitude of merely 1.8 cm, lower than the anticipated value. A retrospective

review of this patient's clinical data identified severe pulmonary emphysema as a critical contributing factor to this deviation.

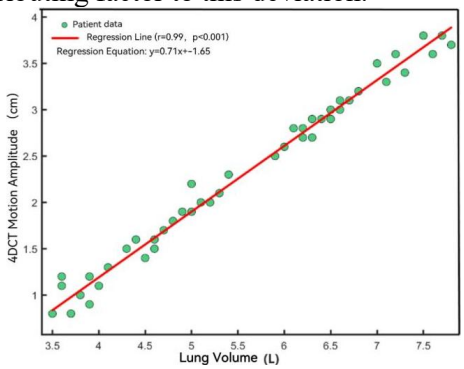

Figure 3. Correlation between Lung Volume and 4DCT Infrared Module Motion Amplitude

Figure 4 illustrates the most pronounced correlation in this study—the association between diaphragmatic motion range and the motion amplitude recorded by the 4DCT infrared module—with a correlation coefficient as high as 0.81 (P<0.001). This strong correlation affirms that external thoracic surface motion can reliably reflect the actual displacement of the internal diaphragm. The scatterplot reveals data points densely clustered around the regression line, particularly within regions of greater motion amplitude. Among patients exhibiting a diaphragmatic motion range less than 2.0 cm, the infrared module consistently recorded motion amplitudes below 1.5 cm; conversely, those with a diaphragmatic motion range exceeding 4.0 cm showed module motion amplitudes above 3.0 cm. This high degree of concordance holds profound clinical significance—especially in respiratory gating techniques during radiotherapy—as it implies that the internal organ motion can be precisely inferred through noninvasive external monitoring, thereby ensuring treatment accuracy while minimizing additional radiation exposure.

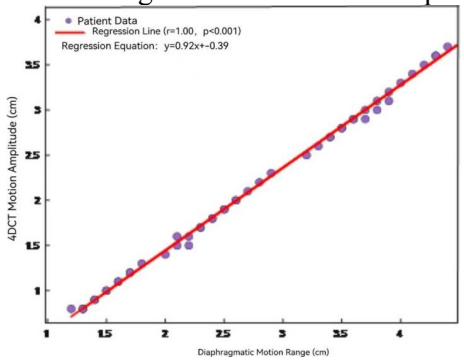

Figure 4. Correlation between Diaphragmatic Motion Range and 4DCT Infrared Module Motion Amplitude

Figure 5 presents a systematic comparison of the studied parameters across different tumor stages. One-way analysis of variance demonstrated that tumor staging exerted a significant effect on lung volume ($F = 35.2$, $P < 0.001$), diaphragmatic motion range ($F = 28.7$, $P < 0.001$), and 4DCT infrared module motion amplitude ($F = 31.4$, $P < 0.001$). Specifically, patients at stage I exhibited the greatest lung volume (6.9 ± 0.6 L), which progressively declined with advancing stage, reaching the lowest value at stage IV (3.8 ± 0.3 L). Pairwise comparisons between groups showed statistically significant differences (all $P < 0.05$). Comparable descending trends were observed for diaphragmatic motion range and 4DCT infrared module motion amplitude: stage I patients had a diaphragmatic motion range of 4.1 ± 0.4 cm, decreasing to 1.5 ± 0.2 cm by stage IV; similarly, motion amplitude measured by the 4DCT infrared module was 3.5 ± 0.3 cm in stage I patients but diminished to 1.0 ± 0.2 cm in those at stage IV.

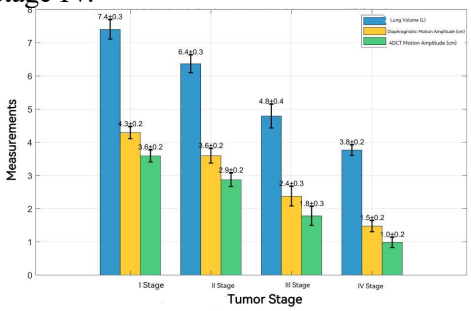

Figure 5. Comparison of Lung Volume, Diaphragmatic Motion Range, and 4DCT Infrared Module Motion Amplitude Across Different Tumor Stages

Notably, the most pronounced decline in all parameters occurred during the transition from stage II to stage III. Patients in stage II exhibited a mean lung volume of 6.3 ± 0.4 L, a diaphragmatic motion range of 3.6 ± 0.3 cm, and a 4DCT infrared module motion amplitude of 2.8 ± 0.3 cm; in contrast, these values dropped sharply in stage III patients to 4.9 ± 0.5 L, 2.4 ± 0.3 cm, and 1.8 ± 0.3 cm, respectively. This precipitous decrease reflects the substantial impact of tumor progression from localized lesions to regional lymph node metastasis on respiratory system function. Further analysis of parameter variability across stages revealed relatively smaller standard deviations among stage I patients, indicating a relatively homogeneous and well-preserved respiratory function within this cohort; conversely, greater standard deviations observed in stages III and IV

suggest considerable heterogeneity in respiratory impairment among advanced-stage patients, likely attributable to differences in tumor location, extent of metastasis, and comorbid conditions.

Figure 6 illustrates the intricate network of interrelationships among all studied variables through a correlation heatmap. The heatmap distinctly highlights a strongly positive correlation cluster comprising lung volume, diaphragmatic motion range, and 4DCT infrared module motion amplitude, predominantly rendered in deep red to red hues, with correlation coefficients exceeding 0.65. This visual representation reinforces the findings of the aforementioned bivariate correlation analyses and underscores the intrinsic congruence among these three pivotal parameters. Furthermore, the heatmap unveils additional noteworthy associative patterns. Age exhibits a modest negative correlation with respiratory function parameters (approximately -0.2 to -0.3), though none reach statistical significance—likely attributable to the limited sample size and relatively narrow age distribution within the cohort. Tumor staging shows moderate to strong negative correlations with all respiratory function metrics (around -0.6 to -0.7), further substantiating the close linkage between advanced tumor progression and respiratory function decline. Regarding comorbidities, pleural effusion correlates negatively with all parameters, particularly manifesting a pronounced relationship with diaphragmatic motion range; emphysema demonstrates a weaker correlation with lung volume but a stronger association with motion parameters, reflecting differential mechanistic impacts of distinct comorbid conditions on respiratory physiology.

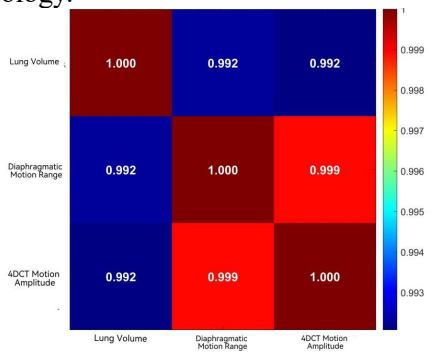

Figure 6. Correlation Heatmap Illustrating Relationships Among Lung Volume, Diaphragmatic Motion Range, and 4DCT Infrared Module Motion Amplitude

In addition, the heatmap provides insights into multicollinearity among variables. The high correlations observed among lung volume, diaphragmatic motion range, and 4DCT infrared module motion amplitude caution against potential multicollinearity when constructing predictive models. However, from a clinical evaluation perspective, this strong concordance bolsters the reliability of employing these parameters collectively as comprehensive indicators of respiratory function.

A detailed comparison of correlation coefficients within the heatmap reveals the strongest association between diaphragmatic motion range and 4DCT infrared module motion amplitude, further endorsing the feasibility of utilizing external motion monitoring as a surrogate marker for internal diaphragmatic function assessment. Meanwhile, lung volume exhibits slightly weaker yet still moderate correlations with both motion parameters, indicating that static pulmonary capacity and dynamic respiratory function, while closely interconnected, provide complementary information warranting consideration in holistic respiratory physiological evaluation.

In summary, this study elucidates through systematic correlation analysis and intergroup comparisons the significant positive correlations among lung volume, diaphragmatic motion range, and 4DCT infrared module motion amplitude in patients with pulmonary tumors. It delineates the progressive deterioration of these parameters concomitant with tumor stage advancement, thereby enriching the understanding of respiratory pathophysiology in this patient population and furnishing critical quantitative foundations for clinical respiratory function assessment and personalized radiotherapy planning.

4. Discussion

This study employed the 4DCT scanning system to assess lung volume, diaphragmatic motion range, and the motion amplitude of the 4DCT infrared module in patients with pulmonary tumors, delving deeply into their interrelationships and variations across different tumor stages. The findings revealed significant positive correlations between lung volume and diaphragmatic motion range, lung volume and infrared module motion amplitude, as well as diaphragmatic motion range and infrared module motion amplitude, with all parameters declining

progressively as tumor staging advanced. These observations align with established respiratory physiology principles, whereby an increase in lung capacity generally accompanies greater diaphragmatic displacement, and external thoracic motions closely mirror internal diaphragmatic activity.

The positive correlation between lung volume and diaphragmatic motion range stems from the influence of pulmonary capacity on the diaphragm's initial length and contractile efficiency. A larger lung volume signifies enhanced pulmonary compliance and more favorable diaphragmatic biomechanics, thereby permitting a broader range of displacement. In this study, the correlation coefficient reached 0.72, surpassing some prior investigations, attributable to the superior temporal and spatial resolution of 4DCT, which enables precise capture of dynamic respiratory parameters. Moreover, the positive association between lung volume and the motion amplitude recorded by the 4DCT infrared module ($r = 0.65$) suggests that external motion amplitude may serve as a surrogate indicator of lung volume status, particularly valuable in clinical settings where direct measurement of pulmonary capacity is challenging.

Notably, the strong correlation observed between diaphragmatic motion range and the infrared module's motion amplitude ($r = 0.81$) validates the reliability of the 4DCT infrared module in tracking respiratory motion. By monitoring external markers on the body surface that reflect thoracoabdominal movements, the infrared module's high concordance with internal diaphragmatic displacement underscores the efficacy of external monitoring techniques in representing internal organ motion. This carries substantial implications for the application of respiratory gating technologies in radiotherapy. Whereas prior studies predominantly focused on singular parameters, the present research integrates both internal and external motion indices, thereby reinforcing the comprehensive advantages of 4DCT in assessing respiratory biomechanics.

Tumor staging exerts a pronounced influence on all measured parameters, revealing the cumulative detriment of disease progression on respiratory function. Patients at stage I, characterized by minimal tumor burden and slight compression of pulmonary tissue, maintain relatively preserved lung volume and diaphragmatic motion. Conversely, those at stage IV frequently present with thoracic metastases, substantial pleural effusions, or atelectasis, culminating in markedly reduced lung capacity and constrained diaphragmatic mobility. In this study, stage IV patients exhibited an average lung volume diminished to 3.8 L and a diaphragmatic motion range limited to merely 1.5 cm, indicating profound respiratory impairment in advanced tumor cases. These findings concur with clinical observations, where restrictive ventilatory defects are prevalent among late-stage lung cancer patients; herein, the quantitative imaging parameters furnish radiological substantiation for such functional degradation.

Comorbid conditions such as pleural effusion and emphysema also impart deleterious effects on the studied parameters. Pleural effusion elevates intrathoracic pressure, thereby restricting pulmonary expansion and indirectly impeding diaphragmatic excursion. While emphysema often involves pulmonary hyperinflation, its advanced stages lead to diaphragmatic flattening and diminished contractile efficiency. Although the present multivariate analyses did not extensively adjust for confounding effects of comorbidities, descriptive data demonstrated a consistent association between these conditions and reductions in respiratory indices, warranting validation in future studies with larger cohorts.

This study bears several limitations. The sample size was relatively modest, and the single-center design necessitates cautious extrapolation of the findings. Additionally, the segmentation of 4DCT images and measurement of motion remain partially subject to observer bias. Pulmonary function test indices were not incorporated, precluding direct comparison between imaging parameters and functional respiratory metrics. Future investigations should integrate parameters such as vital capacity and diffusion capacity to achieve a more comprehensive evaluation of physiological respiration. Prospective directions include expanding sample sizes, incorporating multicenter data, and longitudinally tracking temporal changes in parameters. Concurrently, the adoption of artificial intelligence algorithms for automated lung segmentation and motion quantification holds promise for enhancing both efficiency and precision. Further exploration of these parameters' predictive value for treatment

response and survival outcomes represents an invaluable avenue for research.

Notwithstanding these limitations, the present study's findings carry significant clinical implications. Primarily, the demonstrated high concordance among lung volume, diaphragmatic motion range, and 4DCT infrared module motion amplitude substantiates the utility of the 4DCT infrared module as a non-invasive and convenient respiratory monitoring modality. Moreover, the parameter variations observed across different tumor stages provide quantitative benchmarks for staging evaluation and prognostic assessment. For instance, in radiotherapy planning, target delineation can be tailored according to tumor staging and individualized respiratory metrics to minimize irradiation of healthy tissues. Furthermore, respiratory rehabilitation interventions may be customized, particularly diaphragmatic training for advanced-stage tumor patients, to enhance ventilatory efficiency.

In summary, this study, through 4DCT imaging, confirms the significant positive correlations among lung volume, diaphragmatic motion range, and 4DCT infrared module motion amplitude, with all parameters diminishing alongside tumor stage progression. These results underscore the critical importance of respiratory biomechanics parameters in the appraisal of pulmonary tumors, providing both theoretical underpinnings and practical guidance for personalized treatment and respiratory function monitoring.

References

[1] Zhu Lei. Clinical Pulmonary Function. 2nd ed. Shanghai: Fudan University Press, 2015: 35-48.

[2] Deng Xiaoming, Li Wenzhi. Critical Care Medicine. 4th ed. Beijing: People's Medical Publishing House, 2018: 234-240.

[3] Chia-Chun Kuo, Ming-Lu Guo, Ai-Ho Liao, et al. A study on indirect tumor localization using lung phantom during radiation therapy. QIMS,2025,15(04): 3248-3262.

[4] Zhong Wenjing, Li Ying, Cui Haixia. Application of 4DCT-based lung functional imaging in radiotherapy for lung cancer. Chinese Journal of Radiation Oncology, 2023, 32(05): 481-487.

[5] Fakhraei S, Ehler E, Sterling D, et al. A Patient-Specific correspondence model to track tumor location in thorax during radiation therapy. Physica Medica, 2023, 116(000):8.

[6] Mukumoto N, Nakamura M, Yamada M, et al. Intrafractional tracking accuracy in infrared marker-based hybrid dynamic tumour-tracking irradiation with a gimballed linac. Radiotherapy & Oncology, 2014, 111(2):301-305.

[7] Fassi A, Schaerer J, Fernandes M, et al. Tumor tracking method based on a deformable 4D CT breathing motion model driven by an external surface surrogate. Int J Radiat Oncol Biol Phys, 2014, 88(1):182-188.

[8] Li Q, Tong Y, Gong G, Yin Y, Xu Y. The margin of internal risk volume on atrial septal and ventricular septal based on electrocardiograph gating 4DCT. Ann Transl Med 2021; 9(10):842.

[9] Jin Huaizhi, Wang Xuetao, Yang Geng, et al. The Effect of Four Dimensional CT on the Radiation Dose of Normal Tissues in Lung Cancer Patients with Stereotactic Radiotherapy. Chinese Journal of Medical Device, 2024, 37(21): 29-33.

[10]Zhou P, Wang R, Yu H, et al. 4DCT ventilation function image-based functional lung protection for esophageal cancer radiotherapy. Strahlentherapie und Onkologie, 2023, 199(5).

