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Comparison of CT Radiation Dose Indices in Examinations Associated with Solid and Part-Solid Pulmonary Nodules

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Abstract

Background: Chest computed tomography (CT) is essential for the detection and follow-up of pulmonary nodules, but repeated examinations require radiation dose optimization while maintaining diagnostic image quality. The relationship between pulmonary nodule type and CT radiation dose indices remains insufficiently investigated.
Objective: To compare CTDIvol and SSDE between chest CT examinations associated with non-calcified solid and part-solid pulmonary nodules while accounting for the correlation among multiple nodules within the same patient.
Materials and Methods: A retrospective comparative study included 99 non-calcified pulmonary nodules from 51 patients, comprising 63 solid nodules (63.6%) and 36 part-solid nodules (36.4%). Patient age, nodule type, CTDIvol, and SSDE were recorded. A Generalized Estimating Equations (GEE) model was used with Patient ID as the clustering unit. Statistical significance was set at $p < 0.05$.
Results: Mean age was 57.37 ± 16.90 years for solid nodules and 66.56 ± 14.24 years for part-solid nodules. Mean CTDIvol was 6.06 ± 2.05 mGy and 6.09 ± 1.75 mGy, respectively, while mean SSDE was 7.77 ± 2.34 mGy and 7.52 ± 2.24 mGy, respectively. After accounting for within-patient clustering, no statistically significant differences were observed in age (mean difference: 0.14 years; 95% CI: −0.04 to 0.32; $p = 0.117$), CTDIvol (0.03 mGy; 95% CI: −0.36 to 0.42; $p = 0.891$), or SSDE (−0.01 mGy; 95% CI: −0.07 to 0.06; $p = 0.874$).
Conclusion: No statistically significant differences in CTDIvol or SSDE were found between non-calcified solid and part-solid pulmonary nodules after accounting for within-patient correlation. Nodule type was not associated with the radiation dose indices investigated. These findings highlight the importance of accounting for clustered observations and optimizing chest CT protocols to balance radiation dose and diagnostic image quality.
Keywords: Computed tomography; pulmonary nodules; solid nodules; part-solid nodules; CTDIvol; SSDE; radiation dose; dose optimization.

الملـــخص

الخلفية: يُعد التصوير المقطعي المحوسب للصدر (CT) أساسيًا للكشف عن العقيدات الرئوية ومتابعتها، إلا أن تكرار الفحوصات يتطلب تحسين جرعة الإشعاع مع الحفاظ على جودة الصورة التشخيصية. ولا تزال العلاقة بين نوع العقيدة الرئوية ومؤشرات جرعة الإشعاع في التصوير المقطعي المحوسب غير مدروسة بشكل كافٍ.
الهدف: مقارنة مؤشري جرعة التصوير المقطعي الحجمي (CTDIvol) وتقدير الجرعة النوعية للحجم (SSDE) بين فحوصات التصوير المقطعي المحوسب للصدر المرتبطة بالعقيدات الرئوية الصلبة غير المتكلسة والعقيدات الرئوية الجزئية الصلابة، مع مراعاة الارتباط بين العقيدات المتعددة الموجودة لدى المريض نفسه.

المواد والطرق :أُجريت دراسة مقارنة استعادية شملت 99 عقيدة رئوية غير متكلسة لدى 51 مريضًا، منها 63 عقيدة صلبة (63.6%) و36 عقيدة جزئية الصلابة (36.4%). تم تسجيل عمر المريض، ونوع العقيدة، ومؤشري CTDIvol و SSDE. واستُخدم نموذج المعادلات التقديرية المعممة(GEE) ، مع اعتماد معرّف المريض (Patient ID) كوحدة للتجميع العنقودي. وتم تحديد مستوى الدلالة الإحصائية عند $p < 0.05$

النتائج :بلغ متوسط العمر 57.37 ± 16.90 سنة في مجموعة العقيدات الصلبة، و66.56 ± 14.24 سنة في مجموعة العقيدات الجزئية الصلابة. وبلغ متوسط CTDIvol مقدار 6.06 ± 2.05 mGy و6.09 ± 1.75 mGy ، على التوالي، بينما بلغ متوسط SSDE مقدار 7.77 ± 2.34 mGy و7.52 ± 2.24 mGy ، على التوالي. وبعد مراعاة التجميع العنقودي داخل المريض، لم تُلاحظ فروق ذات دلالة إحصائية في العمر فرق المتوسط: 0.14 سنة؛ فاصل الثقة 95%: −0.04 إلى 0.32؛ $p = 0.117$، أو CTDIvol 0.03 mGy ؛ فاصل الثقة 95%: −0.36 إلى 0.42؛ $p = 0.891$، أو SSDE −0.01 mGy؛ فاصل الثقة 95%: −0.07 إلى 0.06؛ $p = 0.874$

الاستنتاج :لم تُسجل فروق ذات دلالة إحصائية في مؤشري CTDIvol و SSDEبين العقيدات الرئوية الصلبة غير المتكلسة والعقيدات الجزئية الصلابة غير المتكلسة بعد مراعاة الارتباط داخل المريض. ولم يرتبط نوع العقيدة بمؤشرات جرعة الإشعاع التي تم تقييمها. وتبرز هذه النتائج أهمية مراعاة البيانات المترابطة عنقوديًا، وتحسين بروتوكولات التصوير المقطعي المحوسب للصدر لتحقيق التوازن بين جرعة الإشعاع وجودة الصورة التشخيصية.

الكلمات المفتاحية :التصوير المقطعي المحوسب؛ العقيدات الرئوية؛ العقيدات الصلبة؛ العقيدات الجزئية الصلابة؛ CTDIvol؛SSDE ؛ جرعة الإشعاع؛ تحسين الجرعة.

1. Introduction

Pulmonary nodules are common findings on chest computed tomography (CT) examinations and may represent benign lesions or clinically significant abnormalities requiring evaluation and follow-up. CT plays a central role in the detection and characterization of pulmonary nodules based on features such as size, shape, attenuation, and internal appearance. According to their CT appearance, pulmonary nodules are generally classified as solid or subsolid, with subsolid nodules including ground-glass and part-solid nodules. Accurate differentiation between these categories is important for radiological assessment and for determining appropriate follow-up strategies (MacMahon et al., 2017; Revel et al., 2018; Ridge et al., 2016).

The Fleischner Society has established evidence-based recommendations for the management of incidentally detected pulmonary nodules, with follow-up strategies based on nodule size, appearance, and patient risk factors. These recommendations aim to facilitate the early detection of clinically significant lesions while reducing unnecessary follow-up examinations (MacMahon et al., 2017). The importance of CT in pulmonary nodule detection and follow-up has also been supported by studies demonstrating the ability of low-dose CT to detect and evaluate pulmonary nodules while reducing radiation exposure (Diederich et al., 1999; Hu et al., 2021).

Although CT provides substantial diagnostic value, its use of ionizing radiation makes dose optimization particularly important, especially for patients requiring repeated examinations. Low-dose and ultra-low-dose CT protocols have demonstrated the potential to reduce radiation exposure while maintaining adequate diagnostic performance for pulmonary nodule detection and follow-up (National Lung Screening Trial Research Team, 2011; Paks et al., 2018; Gheysens et al., 2022; Gobi et al., 2022). Therefore, CT protocols should achieve an appropriate balance between radiation dose and diagnostic image quality.

Several quantitative indices are used to characterize radiation dose in CT examinations. CTDIvol (Volume CT Dose Index) is widely used to describe CT scanner radiation output associated with a specific examination protocol. However, CTDIvol does not directly account for differences in patient size. The Size-Specific Dose Estimate (SSDE) was therefore introduced to provide a more patient-size-specific estimate of radiation dose by applying appropriate size-related conversion factors to CTDIvol (American Association of Physicists in Medicine, 2011). The use of patient size information, including the Water-Equivalent Diameter (WED), further improves the estimation of SSDE and the interpretation of patient radiation exposure (American Association of Physicists in Medicine, 2014). Accordingly, the combined use of CTDIvol and SSDE provides complementary information for evaluating radiation dose in CT examinations.

Radiation dose during CT is influenced by several technical and patient-related factors, including tube voltage (kVp), tube current–time product (mAs), pitch, scan length, patient size, Automatic Exposure Control (AEC), scanner characteristics, and the imaging protocol. Consequently, differences in pulmonary nodule morphology do not necessarily imply differences in radiation dose, as dose levels may be more strongly determined by examination parameters, patient characteristics, and protocol selection. Previous studies have demonstrated that reducing CT dose can be achieved while maintaining adequate nodule detectability and image quality when appropriate protocols and reconstruction techniques are used (Hu et al., 2021; Vardhanabhuti et al., 2017; Paks et al., 2018).

An additional methodological consideration arises when multiple pulmonary nodules are present in the same patient. Nodules within the same patient may share characteristics such as age, patient size, and examination-related factors, and multiple nodules may originate from the same CT examination. Therefore, the observations cannot necessarily be considered statistically independent. Failure to account for within-patient correlation may lead to inappropriate estimates of standard errors and statistical significance. Accounting for this correlation is consequently important when investigating the relationship between pulmonary nodule type and radiation dose indices.

Despite the importance of radiation dose assessment in chest CT and the increasing use of low-dose protocols for pulmonary nodule follow-up, the relationship between nodule type and radiation dose indices in examinations associated with non-calcified solid and part-solid pulmonary nodules remains insufficiently investigated. Therefore, the present study aimed to compare CTDIvol and SSDE between chest CT examinations associated with non-calcified solid and part-solid pulmonary nodules while accounting for the correlation among multiple nodules within the same patient using a Generalized Estimating Equations (GEE) model.

2. Materials and Methods

2.1 Study Design

This study was conducted as a retrospective comparative study based on the analysis of previously acquired imaging data from computed tomography (CT) examinations, with the aim of comparing radiation dose indices between chest CT examinations associated with non-calcified solid and part-solid pulmonary nodules. The data were not collected directly from a hospital or medical center; rather, they were obtained from an imaging dataset made available for scientific research through The Cancer Imaging Archive (TCIA). The study used the official Low Dose CT Image and Projection Data (LDCT-and-Projection-data), Version 7 dataset available through TCIA (*McCollough et al., 2020*). The dataset contains low-dose CT imaging data of the head, chest, and abdomen and includes a total of 299 CT examinations, with imaging data acquired using CT scanners manufactured by Siemens and GE (McCollough et al., 2020). The study data were accessed through Digital Imaging and Communications in Medicine (DICOM) imaging files available within the dataset. The available CT examinations in the dataset were reviewed, and chest CT examinations containing non-calcified pulmonary nodules and meeting the predefined inclusion criteria of the study were selected. Based on their appearance on CT images, the pulmonary nodules were classified into non-calcified solid nodules and non-calcified subsolid nodules. Data related to nodule type, patient age, and the radiation dose indices CTDIvol and SSDE were extracted from the available DICOM files and examination data within the dataset. The Patient ID was also used to link multiple nodules belonging to the same patient in order to account for the potential correlation among observations from the same patient during statistical analysis using the Generalized Estimating Equations (GEE) model. Because the study relied on retrospective imaging data available through a publicly accessible research database, no additional imaging examinations were performed and no data were collected directly from patients. The analysis was limited to the data available within the dataset and the DICOM files used in the study. Only non-identifiable data available for scientific research purposes were used, with appropriate consideration given to patient privacy and confidentiality.

2.2 Study Population and Sample Size

The study sample consisted of 99 non-calcified pulmonary nodules identified and evaluated on chest computed tomography (CT) examinations. The sample included 63 non-calcified solid pulmonary nodules (63.6%) and 36 non-calcified part-solid pulmonary nodules (36.4%). These nodules represented 51 unique patients, with some patients having more than one pulmonary nodule. In some cases, patients had both solid and part-solid nodules. The pulmonary nodule was considered the primary unit of observation in the study, while the Patient ID was retained for each nodule to identify observations belonging to the same patient and to account for the potential correlation among these observations during statistical analysis. Data associated with each nodule were recorded, including nodule type, patient age, and the radiation dose indices CTDIvol and SSDE. All eligible nodules were retained for analysis, without assuming statistical independence among observations from the same patient.

2.3 Study Variables and Radiation Dose Indices

The study variables included pulmonary nodule type, classified as non-calcified solid and part-solid nodules, patient age measured in years, and the radiation dose indices CTDIvol and SSDE, both measured in mGy. CTDIvol and SSDE were adopted as the primary indices for assessing radiation dose associated with chest CT examinations. CTDIvol represents a standardized index for describing radiation dose output during a CT examination, whereas SSDE incorporates patient size when interpreting the estimated radiation dose. The values of the two radiation dose indices were analyzed and compared between the solid and part-solid nodule groups while accounting for the correlation among multiple nodules within the same patient.

2.4 Data Collection

Data on patient age, nodule type, and the radiation dose indices CTDIvol and SSDE were extracted from the chest computed tomography (CT) examination dataset. The Patient ID was also used to link multiple nodules belonging to the same patient, thereby allowing the clustered structure of the data to be accounted for during statistical analysis.

2.5 Inclusion and Exclusion Criteria

Inclusion and exclusion criteria were predefined to ensure sample homogeneity, availability of the required data, and suitability for achieving the objectives of the study and conducting the statistical analysis. Case selection was based on the available images, demographic data, and radiation dose information contained in the DICOM files within the Low Dose CT Image and Projection Data (LDCT-and-Projection-data) dataset from The Cancer Imaging Archive (TCIA).

2.5.1 Inclusion Criteria

Chest CT examinations were included in the study if they met all of the following criteria:

- The examination was a chest computed tomography (CT) scan.
- At least one non-calcified pulmonary nodule was present and could be classified on CT images.
- The nodule was classified as either a solid or part-solid nodule.
- The CTDIvol value associated with the examination was available.
- The SSDE value was available in the radiation dose data associated with the examination.
- A Patient ID was available, allowing identification of patients with multiple nodules and linkage of observations belonging to the same patient.

2.5.2 Exclusion Criteria

Examinations or nodules meeting any of the following criteria were excluded:

- Presence of a calcified pulmonary nodule or a nodule that could not be clearly classified as either solid or part-solid.
- Absence of the CTDIvol value associated with the examination.
- Absence of the SSDE value in the radiation dose data associated with the examination.
- Incomplete essential data required for analysis, including nodule type, patient age, or Patient ID.
- Examinations that did not fall within the scope of the study or did not meet the predefined analytical requirements.

After applying the inclusion and exclusion criteria, the final analysis included 99 non-calcified pulmonary nodules from 51 patients, comprising 63 solid nodules and 36 part-solid nodules. Multiple nodules belonging to the same patient were retained in the analysis, with the within-patient correlation among observations accounted for during statistical analysis using the Generalized Estimating Equations (GEE) model.

2.6 Statistical Analysis

Statistical analysis was performed using IBM SPSS Statistics. Descriptive statistics included the mean, standard deviation, median, minimum, and maximum for continuous variables, as well as frequencies and percentages for categorical variables. The Shapiro–Wilk test was used to assess the distribution of continuous variables. Because some patients had more than one pulmonary nodule, potentially resulting in correlation among observations from the same patient, all nodules were not treated as statistically independent observations in the inferential analysis. Instead, a Generalized Estimating Equations (GEE) model was used with an exchangeable correlation structure, with Patient ID specified as the clustering unit to account for the correlation among multiple nodules within the same patient. A Gaussian model with an identity link function was used to compare age, CTDIvol, and SSDE between non-calcified solid and part-solid pulmonary nodules, with nodule type specified as the primary independent variable. Sandwich robust standard errors were used to obtain estimates that were more appropriate in the presence of within-patient correlation. Estimated mean differences, 95% confidence intervals (95% CIs), and p-values were reported. Statistical significance was set at $p < 0.05$.

3. Results

3.1 General Characteristics of the Study Sample

The study included 99 non-calcified pulmonary nodules from 51 unique patients. Non-calcified solid pulmonary nodules accounted for 63.6% (63 nodules) of the sample, whereas non-calcified part-solid pulmonary nodules accounted for 36.4% (36 nodules). The dataset included patients with more than one pulmonary nodule, and some patients had both solid and part-solid nodules. Therefore, the correlation among nodules belonging to the same patient was taken into account during the inferential statistical analysis.

3.2 Descriptive Statistics of the Study Variables

The mean age was 57.37 ± 16.90 years in the solid nodule group, with a median of 59 years and a range of 17–86 years, whereas the mean age in the part-solid nodule group was 66.56 ± 14.24 years, with a median of 69 years and a range of 22–86 years. For CTDIvol, the mean value was 6.06 ± 2.05 mGy in the solid nodule group compared with 6.09 ± 1.75 mGy in the part-solid nodule group. The mean SSDE values were 7.77 ± 2.34 mGy and 7.52 ± 2.24 mGy, respectively.

Table 1. Descriptive Statistics of the Study Variables

Variable	Solid Nodules (n=63)	Part-Solid Nodules (n=36)
Age, mean ± SD (years)	57.37 ± 16.90	66.56 ± 14.24
Age, median (years)	59	69
Age, range (years)	17–86	22–86
CTDIvol, mean ± SD (mGy)	6.06 ± 2.05	6.09 ± 1.75
CTDIvol, median (mGy)	6.38	6.57
CTDIvol, range (mGy)	1.59–10.44	2.28–9.39
SSDE, mean ± SD (mGy)	7.77 ± 2.34	7.52 ± 2.24
SSDE, median (mGy)	7.80	8.38
SSDE, range (mGy)	2.73–13.81	3.35–13.81

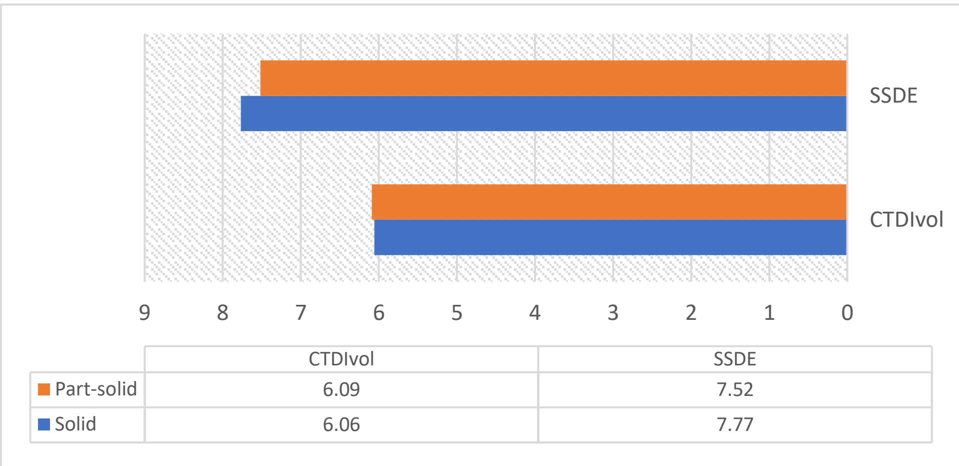

Figure 1. Comparison of CTDIvol and SSDE between solid and part-solid pulmonary nodules

3.3 Statistical Comparison Between the Nodule Groups

Statistical comparisons between the non-calcified solid and part-solid pulmonary nodules were performed using a Generalized Estimating Equations (GEE) model, with Patient ID specified as the clustering unit to account for the potential correlation among multiple nodules within the same patient. The solid nodule group was considered the reference category, and the estimated mean differences represented the comparison between the part-solid and solid nodule groups. The descriptive statistics showed a difference in mean age between the two groups. The mean age was 57.37 ± 16.90 years among patients associated with solid nodules, compared with 66.56 ± 14.24 years among patients associated with part-solid nodules. The descriptive statistics also showed similar mean values for the two radiation dose indices. The mean CTDIvol was 6.06 ± 2.05 mGy in the solid nodule group versus 6.09 ± 1.75 mGy in the part-solid nodule group, while the mean SSDE values were 7.77 ± 2.34 mGy and 7.52 ± 2.24 mGy, respectively. When inferential analysis was performed using the GEE model while accounting for within-patient clustering, no statistically significant difference in age was observed between the two nodule groups. The estimated mean difference in age, comparing part-solid nodules with solid nodules, was +0.14 years, with a 95% confidence interval ranging from −0.04 to +0.32 years; the difference was not statistically significant ($p = 0.117$). For the volume CT dose index (CTDIvol), no statistically significant difference was observed between the two groups. The estimated mean difference was +0.03 mGy, with a 95% confidence interval ranging from −0.36 to +0.42 mGy ($p = 0.891$). Similarly, the size-specific dose estimate (SSDE) showed no statistically significant difference between the two groups. The estimated mean difference was −0.01 mGy, with a 95% confidence interval ranging from −0.07 to +0.06 mGy ($p = 0.874$). Thus, after accounting for the correlation among nodules belonging to the same patient, the GEE model results showed no statistically significant differences between non-calcified solid and part-solid nodules in any of the studied variables: age, CTDIvol, or SSDE. These findings indicate that pulmonary nodule type, according to the classification used in this study, was not associated with statistically significant differences in the radiation dose indices investigated within the study dataset.

Table 2. Results of the Generalized Estimating Equations (GEE) Model Comparing the Nodule Groups

Variable	Estimated Mean Difference*	95% Confidence Interval	*p*-value
Age (years)	+0.14	−0.04 to +0.32	0.117
CTDIvol (mGy)	+0.03	−0.36 to +0.42	0.891
SSDE (mGy)	−0.01	−0.07 to +0.06	0.874

* The estimated mean difference was calculated with the solid nodule group as the reference category. The reported values represent the difference between the part-solid nodule group and the solid nodule group.

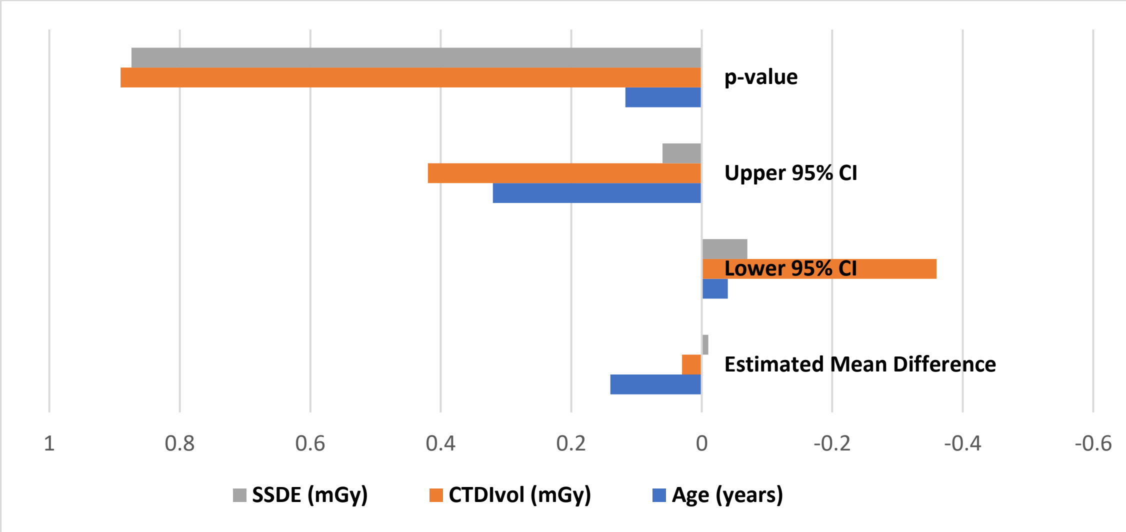

Figure 2. Estimated Mean Differences with 95% Confidence Intervals from the GEE Model Comparing Nodule Groups

4. Discussion

The present study aimed to compare the radiation dose indices CTDIvol and SSDE between non-calcified solid and part-solid pulmonary nodules on chest computed tomography (CT), while accounting for the correlation among multiple nodules within the same patient using a Generalized Estimating Equations (GEE) model. No statistically significant differences were observed between the two groups in age, CTDIvol, or SSDE after accounting for within-patient clustering. These findings suggest that nodule type, according to the classification used in this study, was not associated with significant differences in the radiation dose indices evaluated.

The descriptive analysis showed a higher mean age in the part-solid nodule group than in the solid nodule group; however, the GEE analysis did not demonstrate a statistically significant difference. This finding emphasizes the importance of accounting for within-patient correlation when multiple nodules are present, since treating all nodules as statistically independent observations may result in inappropriate estimates of standard errors and statistical significance.

Regarding radiation dose, CTDIvol showed no statistically significant difference between solid and part-solid nodules. This finding may be explained by the fact that CTDIvol primarily reflects CT scanner output under a specific examination protocol and is therefore influenced mainly by technical and protocol-related factors rather than by the morphological characteristics of the pulmonary nodule itself. Consequently, similar chest CT protocols may produce comparable CTDIvol values regardless of whether the nodule is solid or part-solid.

The present findings are consistent with previous studies supporting the use of low-dose and ultra-low-dose CT for pulmonary nodule assessment and follow-up. Paks et al. (2018) demonstrated the feasibility of ultra-low-dose CT for the follow-up of solid pulmonary nodules while maintaining adequate clinical evaluation and measurement of nodules. Similarly, Gobi et al. (2022) reported that ultra-low-dose CT could reduce radiation exposure while maintaining image quality suitable for the detection and assessment of pulmonary abnormalities. Although these studies did not directly compare solid and part-solid nodules using CTDIvol and SSDE, their findings provide indirect support for the present interpretation that CT examination protocols and dose-reduction strategies may have a greater influence on radiation exposure than nodule morphology itself.

SSDE also showed no statistically significant difference between the two nodule groups. This finding is consistent with the purpose of SSDE, which incorporates patient size into the interpretation of CT radiation dose. AAPM Report 204 emphasized the importance of considering patient size when estimating CT dose, while AAPM Report 220 further supported the use of Water-Equivalent Diameter (WED) as an appropriate measure of patient size for SSDE estimation. Therefore, the similar SSDE values observed in the present study suggest that the morphological differences between solid and part-solid nodules were not associated with a clear difference in patient-size-specific dose estimates.

The findings should be interpreted in the context of previous evidence on dose optimization. Hu et al. (2021) reported that low-dose chest CT could provide adequate pulmonary nodule detection and assessment while reducing radiation exposure compared with standard-dose CT. Similarly, Vardhanabhuti et al. (2017) demonstrated that reducing CT dose can affect nodule detectability depending on factors such as nodule size, nodule type, and body mass index, emphasizing the importance of selecting an appropriate protocol rather than applying a uniform dose strategy. These findings support the concept that CT dose optimization should consider patient and examination characteristics in addition to nodule morphology.

From a clinical perspective, the absence of a statistically significant difference in CTDIvol and SSDE should not be interpreted as evidence that all observed dose levels were optimal. Pulmonary nodule follow-up may require repeated CT examinations; therefore, minimizing unnecessary radiation exposure while maintaining adequate diagnostic image quality is important. The Fleischner Society guidelines emphasize that follow-up strategies should consider nodule size, appearance, and patient risk factors (MacMahon et al., 2017). Accordingly, the imaging protocol should be selected according to the clinical indication and required image quality rather than nodule type alone.

An important distinction between the present study and previous investigations is that the current analysis specifically examined the association between nodule type and CT radiation dose indices while accounting for within-patient correlation using GEE. In contrast, Paks et al. (2018) evaluated the feasibility of ultra-low-dose CT for follow-up of solid pulmonary nodules, while Gobi et al. (2022) investigated ultra-low-dose CT in comparison with standard-dose CT for the detection of pulmonary pathologies. Therefore, these studies should not be interpreted as direct evidence that solid and part-solid nodules have equivalent radiation dose indices; rather, they provide contextual evidence supporting the importance of protocol optimization and dose reduction.

The combined use of CTDIvol and SSDE represents a strength of the present study because these indices provide complementary information regarding scanner output and patient-size-related dose estimation. Another strength was the use of Patient ID and the GEE model to account for the correlation among multiple nodules within the same patient. Nevertheless, the study has several limitations, including the relatively small sample size and reliance on a specific publicly available dataset. Detailed technical parameters, including kVp, mAs, pitch, scan length, and automatic exposure control, were not fully available. In addition, an independent quantitative assessment of image quality was not performed. Therefore, the observed dose levels cannot be considered evidence of an optimal balance between radiation dose and diagnostic image quality.

Overall, the present study found no statistically significant differences in CTDIvol or SSDE between non-calcified solid and part-solid pulmonary nodules after accounting for within-patient correlation. The findings, together with previous evidence from Paks et al. (2018), Gobi et al. (2022), Hu et al. (2021), and Vardhanabhuti et al. (2017), support the importance of using appropriately optimized low-dose CT protocols for pulmonary nodule assessment and follow-up. Dose optimization should consider patient size, scanner and examination parameters, reconstruction techniques, and the required diagnostic image quality rather than relying on nodule type alone. The methodological recommendations of AAPM Reports 204 and 220 provide an appropriate framework for interpreting CTDIvol and SSDE in relation to patient size, while the Fleischner Society recommendations provide the clinical context for pulmonary nodule follow-up.

5. Conclusion

The present study concluded that there were no statistically significant differences between non-calcified solid and part-solid pulmonary nodules in the radiation dose indices CTDIvol and SSDE after accounting for the correlation among multiple nodules within the same patient using a Generalized Estimating Equations (GEE) model. These findings indicate that nodule type itself was not associated with radiation dose level within the study dataset.

The results emphasize the importance of evaluating CT radiation dose within an integrated framework that considers patient size, examination parameters, imaging protocol, and the required image quality, rather than relying solely on nodule type to determine radiation dose level. They also highlight the importance of using CTDIvol and SSDE together when assessing radiation dose, particularly in pulmonary nodule follow-up examinations that may require repeated imaging.

In light of the available evidence, the study supports the adoption of appropriate low-dose CT (LDCT) protocols for follow-up examinations to reduce radiation exposure to the lowest practical level while maintaining sufficient image quality for the intended diagnostic purpose. The study also emphasizes the importance of accounting for the correlation among multiple nodules within the same patient during statistical analysis to provide estimates that are more accurate and appropriate for the structure of the data.

Nevertheless, the findings should be interpreted in light of the relatively limited sample size and the unavailability of some detailed technical examination parameters, as well as the absence of an independent quantitative assessment of image quality. Therefore, future studies are recommended to include larger, multicenter samples with detailed technical examination parameters and quantitative image-quality measures. Such studies may provide a more precise understanding of the relationship among radiation dose, image quality, and nodule type and support the development of optimized and safe protocols for pulmonary nodule follow-up.

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14. The data used in this study were obtained from the official *Low Dose CT Image and Projection Data (LDCT-and-Projection-data), Version 7* dataset available through **The Cancer Imaging Archive (TCIA)** (McCollough et al., 2020). The dataset was accessed through the official TCIA collection page: *https://www.cancerimagingarchive.net/collection/ldct-and-projection-data/*.