Original Article

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Additive Value of Whole-body CT in Patients Imaged with PET/CT for Solitary Pulmonary Nodules

Soliter Pulmoner Nodüller Nedeniyle PET/BT ile Görüntülenen Hastalarda Tüm Vücut BT'nin Ek Değeri

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Abstract

Objectives: In routine positron emission tomography/computed tomography (PET/CT) imaging of solitary pulmonary nodules (SPNs), CT acquisition is typically performed from the vertex to the mid-thigh. The administered ^{18}F-fluorodeoxyglucose (^{18}F-FDG) dose is adjusted according to patient weight and is independent of the scanned body region; however, radiation exposure from the CT component increases with scan length. In this study, we aimed to evaluate the clinical value of extrathoracic CT imaging in patients undergoing PET/CT for SPN characterization and to quantify the potential reduction in radiation dose when CT is limited to the thorax.

Methods: A total of 154 patients who underwent ^{18}F-FDG PET/CT for the evaluation of SPNs between 2009 and 2011 were retrospectively analyzed. None of the patients had a prior diagnosis of malignancy or had received chemotherapy or radiotherapy. Incidental extrathoracic CT findings were classified as major, moderate, or minor according to their clinical significance. CT radiation dose was estimated using dose-length product (DLP) values. PET findings, incidental CT findings, radiation dose, and acquisition times were evaluated.

Results: Extrathoracic CT findings were detected in 61 patients (39%), with a total of 86 incidental lesions. However, only 3 patients (2%) had major extrathoracic findings requiring urgent clinical intervention. Two of these were osteolytic bone lesions that were ^{18}F-FDG avid and potantially detectable on whole-body PET. Extrathoracic ^{18}F-FDG uptake was observed in 10 patients (6.5%). The mean DLP was 458.3±70.5 mGy cm for whole-body CT and 130.8±9.1 mGy cm for thorax-only CT, corresponding to a 3.5-fold higher CT radiation dose ($p<0.01$). A PET-based protocol, however, prolongs acquisition time by approximately 6 minutes.

Conclusion: In SPN PET/CT evaluation, routine body CT does does not provide clinically significant additional information in most patients but substantially increases radiation exposure. Performing thoracic CT following whole-body PET, with additional targeted CT only when extrathoracic PET abnormalities are detected, may reduce radiation exposure while preserving the diagnostic information provided by CT of the thorax. However, such an approach prolongs acquisition time and increases workload.

Keywords: Solitary pulmonary nodule, PET/CT, radiation dose, incidental findings, ^{18}F-FDG

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Öz

Amaç: Soliter pulmoner nodüllerin (SPN) rutin pozitron emisyon tomografisi/bilgisayarlı tomografi (PET/BT) görüntülemesinde, BT çekimi genellikle verteksten uyluk ortasına kadar gerçekleştirilir. Uygulanan ^{18}F-florodeoksiglukoz (^{18}F-FDG) dozu hastanın vücut ağırlığına göre ayarlanır ve taranan vücut bölgesinden bağımsızdır; ancak BT bileşeninden kaynaklanan radyasyon maruziyeti tarama uzunluğuyla artar. Bu çalışmada, SPN karakterizasyonu amacıyla PET/BT yapılan hastalarda toraks dışı BT görüntülemesinin klinik değerini değerlendirmek ve BT'nin toraksla sınırlandırılması durumunda radyasyon dozunda sağlanabilecek azalmayı nicel olarak belirlemek amaçlandı.

Yöntem: SPN değerlendirmesi amacıyla 2009–2011 yılları arasında ^{18}F-FDG PET/BT yapılan toplam 154 hasta retrospektif olarak incelendi. Hastaların hiçbirinde önceden malignite tanısı veya kemoterapi ya da radyoterapi öyküsü yoktu. Toraks dışı insidental BT bulguları, klinik önemlerine göre majör, orta derecede önemli veya minör olarak sınıflandırıldı. BT radyasyon dozu, doz-uzunluk çarpımı (DLP) değerleri kullanılarak tahmin edildi. PET bulguları, insidental BT bulguları, radyasyon dozu ve çekim süreleri değerlendirildi.

Bulgular: Altmış bir hastada (%39) toraks dışı BT bulgusu saptandı ve toplam 86 insidental lezyon belirlendi. Bununla birlikte, yalnızca 3 hastada (%2) acil klinik müdahale gerektiren majör toraks dışı bulgular mevcuttu. Bunlardan ikisi, ^{18}F-FDG tutulumu gösteren ve tüm vücut PET ile potansiyel olarak saptanabilecek osteolitik kemik lezyonlarıydı. On hastada (%6,5) toraks dışı ^{18}F-FDG tutulumu gözlendi. Ortalama DLP, tüm vücut BT için 458,3±70,5 mGy·cm, yalnızca toraks BT için ise 130,8±9,1 mGy·cm idi. Bu değerler, tüm vücut BT'de radyasyon dozunun 3,5 kat daha yüksek olduğunu gösterdi ($p<0,01$). Bununla birlikte, PET temelli bir protokol çekim süresini yaklaşık 6 dakika uzatmaktadır.

Sonuç: SPN PET/BT değerlendirilmesinde rutin tüm vücut BT, hastaların çoğunda klinik açıdan anlamlı ek bilgi sağlamamakta, ancak radyasyon maruziyetini belirgin ölçüde artırmaktadır. Tüm vücut PET sonrasında toraks BT yapılması ve yalnızca toraks dışı PET anormallikleri saptandığında ek hedefe yönelik BT uygulanması, toraks BT'nin sağladığı tanısal bilgiyi korurken radyasyon maruziyetini azaltabilir. Bununla birlikte, bu yaklaşım çekim süresini uzatmakta ve iş yükünü artırmaktadır.

Anahtar Kelimeler: Soliter pulmoner nodül, PET/BT, radyasyon dozu, rastlantısal bulgular, ^{18}F-FDG

Introduction

A solitary pulmonary nodule (SPN) is defined as a round or oval pulmonary opacity measuring less than 3 cm in diameter, completely surrounded by normal lung parenchyma and not associated with atelectasis or lymphadenopathy (1). SPNs are frequently detected incidentally during thoracic imaging and encompass a broad spectrum of etiologies, including malignant, infectious, inflammatory, vascular, and congenital conditions. Accurate characterization is essential, as early detection of lung cancer significantly improves prognosis.

^{18}F-fluorodeoxyglucose positron emission tomography (^{18}F-FDG PET) is an established non-invasive imaging modality for metabolic evaluation of SPNs (2). Hybrid PET computed tomography (CT) combines functional and anatomical information and may improve the characterization of SPNs compared with PET or CT findings alone (3,4). Accordingly, PET/CT is widely incorporated into clinical algorithms for SPN assessment.

In routine oncologic PET/CT protocols, CT acquisition typically extends from the vertex to the mid-thigh. While the administered FDG activity is weight-based and independent of the scanned body region, radiation exposure from the CT component increases proportionally with scan length. Therefore, whole-body CT is a major contributor to the cumulative radiation dose (5).

For patients undergoing ^{18}F-FDG PET/CT to characterize an SPN in the absence of a known malignancy, the primary clinical objective is to determine the metabolic nature of the SPN. Although whole-body PET is essential for detecting potential extrathoracic disease, the necessity of performing CT over the entire scanned region remains uncertain. While extrathoracic CT may reveal incidental findings, the clinical relevance of these findings and their impact on patient management are not well established.

From the perspective of radiation protection, reducing unnecessary CT coverage is consistent with the ALARA (as low as reasonably achievable) principle. Restricting CT acquisition to the thorax, while maintaining whole-body PET imaging, may reduce radiation exposure, although the potential impact on diagnostic performance requires further evaluation. Therefore, this study aimed to evaluate the clinical necessity of extrathoracic CT acquisition during PET/CT for SPN evaluation and quantify the potential reduction in radiation dose when CT is limited to the thoracic region.

Materials and Methods

Study Design and Patient Population

This retrospective study included 154 consecutive patients who were referred to our department between January 2009 and July 2011 for metabolic characterization of a SPN.

Inclusion criteria were as follows: (1) presence of an SPN detected on thoracic CT; (2) no prior history of malignancy; and (3) no history of chemotherapy or radiotherapy prior to PET/CT. Patients with incomplete imaging data were excluded.

This study was conducted in accordance with the principles of the Declaration of Helsinki and was approved by the

Ethics Committee of Gazi University Faculty of Medicine, Ankara (date: 14.12.2011, approval no: 362). Due to the retrospective nature of the study, the requirement for informed consent was waived.

PET/CT Imaging Protocol

All ^{18}F-FDG PET/CT examinations were performed according to the institutional standard oncologic imaging protocol. Patients fasted for at least 6 hours prior to imaging, and blood glucose levels were confirmed to be <200 mg/dL before tracer administration. ^{18}F-FDG was administered intravenously at a dose of 0.14 mCi/kg (5.18 MBq/kg). Imaging was performed 60 minutes after injection using a GE Discovery ST PET/CT system (General Electric Medical Systems, Milwaukee, WI, USA).

A low-dose, non-contrast CT scan was acquired from the vertex to the mid-thigh using the following parameters: tube voltage 120 kV and tube current 10-90 mA with automatic modulation. CT data were used for attenuation correction and anatomical localization.

Subsequently, whole-body PET emission imaging was performed in three-dimensional mode with an acquisition time of 3 minutes per bed position. The intrinsic spatial resolution of the PET system was approximately 5 mm. Images were reconstructed to generate axial, coronal, and sagittal slices with a slice thickness of 3.75 mm.

Image Analysis

All PET/CT studies were independently evaluated by two experienced nuclear medicine physicians. Metabolic activity was quantified using the maximum standardized uptake value (SUV_{max}). Regions of interests (ROIs) were manually drawn on attenuation-corrected images to encompass the entire SPN, and SUV_{max} values were recorded.

Incidental extrathoracic CT findings were classified according to clinical significance as major, moderate, or minor (Table 1) (6). Major findings were defined as those requiring urgent medical or surgical intervention or immediate further investigation; moderate findings as those generally requiring additional evaluation but not posing an immediate health threat; and minor findings as those rarely requiring further workup. This classification was based on previously published criteria.

Radiation Dose Estimation

Radiation exposure from the CT component was estimated using dose-length product (DLP) values obtained from the scanner console. DLP (mGy·cm) was calculated as the product of the volumetric CT dose index (CTDIvol) and scan length (7). CTDI_vol represents a standardized measure of radiation output during CT acquisition (8,9). Effective dose was indirectly assessed using DLP values and established conversion factors. For each patient, CT radiation doses were calculated for both whole-body PET/CT and a hypothetical thorax-only CT acquisition, and the values were compared.

Statistical Analysis

Statistical analyses were performed using SPSS version 10.0 (SPSS Inc., Chicago, IL, USA).

Patients with SPNs confined to the thorax and those with extrathoracic findings were compared in terms of PET/CT findings, CT radiation dose, and scan duration. Normality of data distribution was assessed using the Kolmogorov-Smirnov test.

For normally distributed variables, ANOVA and Student's t-test were used; for non-normally distributed variables, the Mann-Whitney U test and the Kruskal-Wallis test were used. Categorical variables were analyzed using the chi-square test. A p-value <0.05 was considered statistically significant.

Results

A total of 154 patients who underwent ^{18}F-FDG PET/CT for the metabolic characterization of SPNs between January 2009 and July 2011 were included in the study (Table 2).

Table 1. Incidental findings according to clinical significance

Category	Definition	Example
Major findings	Findings requiring urgent intervention or further investigation	Abdominal aortic aneurysm/dissection, massive pleural/pericardial effusion, osteolytic lesion that may cause fracture, pulmonary embolism, some solid masses (pancreas, liver, stomach), ovarian cyst >5cm
Moderate findings	Findings that may require further evaluation but are not clinically significant	Cystic abdominal lesions (pancreatic), thyroid gland lesions, adrenal gland lesions, kidney anomaly, ureteral stone, common bile duct stone, air in the biliary tract
Minor findings	Findings that rarely require further evaluation and are clinically insignificant	Cholelithiasis, nephrolithiasis, urolithiasis, cystic abdominal lesions (hepatic, <5 cm adnexal and renal), vascular calcifications, uterine fibroids, hepatic steatosis

Table 2. Demographic and clinical characteristics of the study population	
Number of patients (n)	**154**
Age (years), mean (± SD)	60.62±11.27
Sex, n (%)	
Female	39 (25.3%)
Male	115 (74.7%)
Sampling type, n (%)	
Cytology only	24 (58%)
Biopsy ± cytology	17 (42%)
SUV_{max} value of the nodule, mean ± SD	1.3±2.6
Size of the nodules, mean (cm) ± SD	1.8±0.7
Histopathology of nodules, n (%)	
Malignant	12 (29.9%)
Benign	2 (4.8%)
Dysplasia	2 (4.8%)
Infectious/inflammatory	6 (14.6%)
Normal	19 (45.9%)
SD: Standard deviation, SUV_{max}: Maximum standardized uptake value	

Histopathological confirmation was available in 41 patients.

No significant difference in mean age was observed between patients with malignant and non-malignant SPNs (F=0.079, p=0.8). Among the 12 histopathologically confirmed malignant lesions, adenocarcinoma was the predominant subtype (n=9), followed by squamous cell carcinoma (n=1) and small cell carcinoma (n=2).

Lesion size was comparable between groups, with a mean diameter of 1.8±0.6 cm in malignant nodules and 1.7±0.7 cm in benign nodules, showing no statistically significant difference (p=0.47).

The mean SUV_{max} of all lesions was 1.3±2.6. Lesions that underwent biopsy or cytological evaluation had a higher mean SUV_{max} compared with those without histopathological assessment (3.9±3.7 vs. 0.4±1.0). Among the lesions with histopathological diagnosis, the mean SUV_{max} was significantly higher in malignant lesions than in benign lesions (5.6±4.0 vs. 2.1±1.9, p=0.014). A significant positive correlation was observed between SUV_{max} and nodule size (r=0.359, p<0.001).

Extrathoracic ^{18}F-FDG uptake was observed on whole-body maximum intensity projection PET images in 10 of 154 patients. A total of 13 lesions were identified: 1 in the adrenal gland, 9 in the gastrointestinal tract, and 3 in the bone. Although pathological ^{18}F-FDG uptake was present, no biopsy was performed on the adrenal lesion. Two osteolytic bone lesions showed CT features suggestive of malignancy; however, histopathological confirmation was not obtained. The third bone uptake was located at the articular surface of the acetabulum and interpreted as degenerative.

Colonoscopy was performed on 4 of the 9 intestinal lesions. Histopathological evaluation revealed a hyperplastic polyp in one case and adenocarcinoma metastasis in another, while no pathological findings were detected in the remaining two cases.

Evaluation of the corresponding CT images in 93 patients showed no incidental findings. In contrast, 86 incidental findings were identified in 61 patients; of these findings, only 3 were classified as major extrathoracic findings (Table 3).

One of the major findings was an abdominal aortic aneurysm with a maximum diameter of 58 mm, which met the threshold for surgical intervention. The other two major findings were destructive osteolytic bone lesions, classified as such because of their associated fracture risk. However, both lesions were ^{18}F-FDG avid and could be detected on whole-body PET imaging without the need for whole-body CT.

A massive pericardial effusion was identified in one case; however, it was not classified as an extrathoracic incidental finding given its intrathoracic location, and it would be detectable on routine thoracic CT performed for SPN evaluation.

A total of 18 findings were categorized as moderate in clinical significance. These included 7 thyroid nodules, 7 adrenal lesions, and 4 renal anomalies (3 atrophic kidneys and 1 pelvic kidney).

The remaining 64 findings, of which 52 were extrathoracic, were classified as minor findings (Table 3).

When whole-body CT was performed, the mean CT-derived radiation dose was 458.3±70.5 mGy. cm. In contrast, the estimated mean radiation dose for a thorax-only CT scan was 130.8±9.1 mGy·cm, corresponding to a 3.5-fold increase in radiation exposure with whole-body CT (p<0.01).

The mean acquisition time for the 154 patients who underwent the standard whole-body PET/CT protocol was 22.5±1.6 minutes. In a hypothetical protocol consisting of whole-body PET followed by thorax-limited PET/CT, with additional targeted CT acquisition of extrathoracic regions when clinically indicated, the mean scan time would increase to 28.9±4.0 minutes (F=329.84, p<0.001).

This approach would result in an approximate increase in scan time of 6 minutes.

Discussion

The routine PET/CT fusion imaging protocol used in our

Table 3. Classification of incidental findings detected by ^{18}F-FDG PET/CT according to the degree of importance			
Incidental findings	**^{18}F-FDG positive, n**	**^{18}F-FDG negative, n**	**Total, n**
Major findings			
Abdominal aortic aneurysm	0	1	1
Massive pericardial effusion	0	1	1
Osteolytic lesion	2	0	2
Moderate findings			
Thyroid nodule	4	3	7
Surrenal lession	1	6	7
Renal anomaly	0	4	4
Minor findings			
Renal cyst (<5 cm)	0	19	19
Hepatic cyst (<5 cm)	0	3	3
Cholelithiasis	0	8	8
Vascular calcifications	0	28	28
Uterine fibroids	0	3	3
Nephrolithiasis	0	3	3
Total	7	79	86

^{18}F-FDG: ^{18}F-fluorodeoxyglucose, PET: Positron emission tomography, CT: Computed tomography

department for the evaluation of SPNs includes scanning the body from the vertex to the mid-thigh. CT not only provides anatomical information about lesions but also enables attenuation correction of PET data and the calculation of SUV_{max} values. For this purpose, low-dose CT is employed.

In patients with known SPNs, thoracic PET/CT fusion imaging is sufficient for accurate metabolic evaluation and SUV_{max} calculation. However, when whole-body scanning is performed, a large portion of the patient's body is exposed to CT-related ionizing radiation, even when low-dose protocols are used. This raises questions regarding the clinical necessity of routine whole-body CT.

The primary purpose of routine whole-body imaging in oncologic practice is to determine disease extent. FDG-avid lesions can be detected by PET imaging. Therefore, when necessary, additional low-dose CT imaging can be selectively performed for extrathoracic regions demonstrating abnormal FDG uptake.

Nevertheless, routine whole-body CT scanning may allow the detection of incidental findings that do not demonstrate FDG uptake. Incidental findings generally refer to unexpected abnormalities that are unrelated to the primary indication for imaging but are potentially clinically relevant (10,11). In the literature, extrathoracic incidental findings on CT are commonly classified into three categories based on their clinical significance: major, moderate, and minor (6,12,13). In our study, we adopted this classification system and categorized incidental findings accordingly (Table 1).

In our cohort, 86 incidental findings unrelated to SPNs were identified in 61 patients (39%). Although this rate appears high, only 3 of these findings (2%) were classified as major, requiring urgent clinical intervention (Table 3).

One of the major findings was an abdominal aortic aneurysm. Elective repair should be considered for asymptomatic abdominal aortic aneurysms measuring ≥5.5 cm in men and ≥5.0 cm in women (14,15). The patient was female, and the aortic diameter measured 5.8 cm, indicating a clear need for surgical intervention.

The other major findings included osteolytic bone lesions associated with an increased risk of fracture. Both lesions were FDG-avid and could be detected on PET imaging alone. When necessary, additional targeted PET/CT imaging may be performed to further evaluate CT morphology and SUV_{max} values.

In a similar study involving 250 patients undergoing PET/CT, the rate of major findings was reported as 3% (16). Unlike our study, the other study included major intrathoracic findings such as massive pleural effusion and pneumothorax. However, since thoracic PET/CT fusion imaging is routinely performed during SPN evaluation, intrathoracic findings can be assessed. Therefore, the case of pericardial effusion in our study was not classified as an

extrathoracic major finding.

Incidental findings of moderate significance in our study were predominantly related to thyroid, adrenal, and renal pathologies. Among the 7 thyroid nodules identified, 3 were FDG-negative and were considered benign, requiring no further evaluation. In contrast, focal FDG uptake was observed in 4 nodules. Previous studies have reported a prevalence of malignancy of approximately 30–35% among FDG-avid thyroid incidentalomas (17,18).

In our study, biopsy was performed in two of these cases, revealing papillary thyroid carcinoma in one and benign nodular hyperplasia in the other. These findings indicate that although FDG uptake increases suspicion for malignancy, not all FDG-avid lesions are malignant. Therefore, PET findings alone are insufficient; additional diagnostic methods, such as ultrasonography and fine-needle aspiration biopsy, should be considered.

Regarding adrenal findings, a total of 7 lesions were detected, only one of which demonstrated FDG uptake. No histopathological confirmation was performed. In the case of FDG-positive adrenal involvement, widespread metastatic disease was observed on PET imaging, and the adrenal lesion was therefore interpreted as metastatic, obviating the need for further evaluation. It is well known that the adrenal glands are a common site of hematogenous metastasis in lung cancer and that metastatic lesions typically demonstrate FDG uptake (19).

FDG-negative adrenal lesions were predominantly small, homogeneous, and low-density nodules, consistent with benign adenomas. In patients without known malignancy, most incidentally detected adrenal lesions are benign, and many represent non-functioning adrenocortical adenomas (20,21,22). Accordingly, the majority of adrenal lesions in our study were considered benign and did not require further investigation.

Renal findings included 3 atrophic kidneys and 1 pelvic kidney, each in a different patient. All patients had normal serum creatinine levels and remained clinically stable during follow-up; therefore, no intervention was required.

Other extrathoracic incidental findings were classified as minor findings. Simple renal cysts, common incidental findings in the general population, were among these (23). According to the Bosniak classification system, renal cysts are categorized into four groups based on CT characteristics to estimate malignancy risk (24). This classification has been shown to be reliable in guiding clinical management. Bosniak category I lesions are simple, benign cysts that require neither treatment nor follow-up. All renal cysts in our study were consistent with category I lesions and were therefore considered clinically insignificant.

Hepatic cystic lesions are thought to arise from congenital biliary duct abnormalities that dilate over time. Simple hepatic cysts are common benign incidental findings on liver imaging (25). In our cohort, all lesions demonstrated imaging features consistent with simple cysts, including well-defined margins, thin walls, and fluid attenuation. Therefore, these findings were considered clinically insignificant, and follow-up was deemed sufficient.

Aortic calcification is closely associated with atherosclerosis and results from endothelial injury and plaque formation in the presence of risk factors such as advanced age, diabetes mellitus, hyperlipidemia, and smoking. Abdominal aortic calcification is a common incidental finding on imaging studies. Several studies have demonstrated a strong association between aortic calcification and coronary artery disease, cardiovascular morbidity, and mortality (26,27). In our study, abdominal aortic calcification was observed in 18% of patients, and coronary artery calcification could also be assessed on the available thoracic PET/CT images. Therefore, the detection of isolated abdominal aortic calcification does not, by itself, warrant routine whole-body CT imaging.

When moderate and minor findings are excluded, whole-body CT did not provide clinically meaningful additional information in approximately 98% of cases.

Medical imaging represents a major source of exposure to ionizing radiation in the general population (28). In diagnostic imaging, stochastic radiation effects are of particular concern, and radiation exposure should be kept as low as reasonably achievable (ALARA) while preserving clinically relevant diagnostic information. Application of the ALARA principle should not result in the loss of potentially valuable diagnostic information when the clinical benefit of reducing radiation exposure has not been adequately established. The CT radiation dose depends on technical parameters such as tube voltage, tube current, and scan duration (29,30). Modern CT systems allow dose optimization according to patient size and anatomy. Although low-dose CT protocols are routinely used in PET/CT, our findings demonstrate that extending CT acquisition from the thorax to the whole-body results in approximately 3.5-fold higher CT radiation exposure compared with thorax-limited CT. This finding emphasizes the contribution of scan length to radiation dose and supports continued efforts to optimize CT coverage and acquisition parameters according to the clinical indication.

Based on our findings, a selective or stepwise imaging strategy may be considered to reduce radiation exposure in carefully selected patients with SPNs and no known history of malignancy. However, this approach should not currently be regarded as a replacement for routine whole-body CT

in all patients. One potential strategy would involve whole-body PET imaging followed by thorax-limited PET/CT, with additional targeted CT acquisition when clinically indicated, particularly in the presence of abnormal extrathoracic FDG uptake. Although this approach increased the estimated acquisition time by approximately 6 minutes in our analysis, it resulted in a substantial reduction in radiation exposure. Prospective and multicenter studies are needed to determine whether such a strategy can maintain diagnostic performance and patient safety while providing a meaningful reduction in radiation exposure.

Importantly, advances in CT technology provide alternative approaches to reducing radiation exposure without necessarily eliminating whole-body CT acquisition. Modern CT systems incorporate improved detector technology, automated exposure control, iterative reconstruction, and increasingly, deep learning-based reconstruction and denoising algorithms. These approaches can reduce image noise and improve image quality in low-dose CT examinations, potentially allowing further reductions in radiation exposure while maintaining clinically acceptable diagnostic performance (31). Recent reviews have also highlighted the potential of deep learning-based denoising techniques to improve the quality of low-dose CT images and facilitate dose reduction (32).

Similarly, advances in PET detector technology, including digital PET systems based on silicon photomultipliers, improved image reconstruction, and deep learning-based denoising, may provide opportunities to reduce administered radiotracer activity while maintaining or improving image quality. Digital PET systems offer higher sensitivity, improved timing and spatial resolution, and better count efficiency than conventional photomultiplier-based PET systems, which may permit shorter acquisition times or lower administered ^{18}F-FDG activity while preserving lesion detectability and quantitative performance. In a clinical study of oncology patients, digital PET/CT reduced acquisition time to 50% of the standard protocol while preserving lesion detection and quantitative PET parameters, supporting potential dose reduction in clinical practice (33).

The CT component of PET/CT plays an important role not only in anatomical localization but also in attenuation correction and quantitative assessment of PET uptake. Therefore, complete elimination of CT-based attenuation correction may affect PET image quality and quantitative accuracy, particularly when evaluating lesions outside the thorax. Nevertheless, recent advances in artificial intelligence have introduced promising approaches for reducing the dependence of PET on CT for attenuation correction. Deep learning-based methods can generate synthetic attenuation maps from non-attenuation-corrected PET data or directly produce attenuation- and scatter-corrected PET images without requiring CT-derived attenuation information (34). Several studies have demonstrated good agreement between deep learning-based CT-free PET and conventional CT-based attenuation-corrected PET, including preservation of SUV distributions and diagnostic image quality (35). However, the performance of these methods may vary depending on tracer, scanner, acquisition protocol, and patient anatomy; issues related to generalizability and robustness remain important barriers to routine clinical implementation (36). Although deep learning-based CT-free attenuation correction may eventually facilitate PET imaging with reduced or no CT-related radiation exposure, these techniques currently remain investigational and should not be considered a replacement for CT-based attenuation correction in routine clinical practice.

Another potential strategy for reducing radiation exposure associated with the CT component of PET/CT is the use of PET/magnetic resonance (MR). Because magnetic resonance imaging (MRI) does not use ionizing radiation, PET/MR can eliminate the CT-related radiation exposure while providing simultaneous metabolic and anatomical information. However, pulmonary imaging remains challenging because of the low proton density of the lungs, short T2 relaxation times, susceptibility effects, and respiratory motion. Recent advances in ultrashort echo time (UTE) and zero echo time (ZTE) MRI techniques have substantially improved the visualization of lung parenchyma and pulmonary nodules. The Fleischner Society has recognised UTE and ZTE techniques as important advantages that have expanded the potential clinical applications of pulmonary MRI, although further validation is required for several applications (37). In a prospective study comparing ZTE-MRI with CT in patients with SPNs or masses larger than 1 cm, ZTE-MRI showed excellent interobserver and intermodality agreement for nodule size and several morphological features although subjective image quality remained superior with CT (38). Nevertheless, PET/MR should not currently be considered a direct replacement for PET/CT in SPN evaluation, particularly when detailed morphological characterization of small pulmonary nodules is required. Further prospective and multicenter studies are needed to determine whether advanced lung MRI techniques can provide sufficient diagnostic information to support the use of PET/MR as a radiation-sparing alternative in selected patients.

Study Limitations

This study has several limitations that should be

acknowledged. First, its retrospective design may have introduced selection bias, and the findings may not be fully generalizable to all patient populations.

Second, histopathological confirmation was not available for all lesions, particularly for incidental extrathoracic findings, which may limit the definitive characterization of some lesions.

Third, the study was conducted at a single center with a relatively small sample size, which may affect the external validity of the results. The prevalence and clinical significance of incidental extrathoracic findings may vary according to patient characteristics, referral patterns, institutional practices, and PET/CT acquisition protocols. Therefore, the observed 2% rate of major extrathoracic findings should be interpreted cautiously and not be considered representative of broader patient populations or healthcare settings. Larger prospective or multicenter retrospective studies involving diverse patient populations and standardized PET/CT protocols are warranted to validate our findings and determine whether a selective or stepwise CT acquisition strategy can be safely implemented in routine clinical practice. In addition, the PET/CT protocol used in this study reflects the technical characteristics and clinical workflow of our institution; variations in imaging protocols across centers may therefore influence the generalizability of our findings.

Another limitation is that the clinical impact of incidental findings was assessed based on imaging and available clinical data, without long-term follow-up for all patients. Therefore, the potential delayed clinical significance of some incidental findings cannot be completely excluded.

Although a hypothetical stepwise imaging protocol was proposed to reduce radiation exposure, this approach was not implemented prospectively, and its impact on diagnostic accuracy, workflow efficiency, and patient outcomes requires further validation in prospective studies.

Conclusion

In the evaluation of SPNs, routine whole-body CT performed as part of PET/CT imaging provides little additional clinically meaningful information in selected patients without a known history of malignancy, while substantially increasing radiation exposure. Although incidental extrathoracic findings may be detected, the vast majority were classified as minor or moderate in our study.

A more tailored imaging strategy, consisting of whole-body PET followed by thorax-limited CT, with additional targeted CT when clinically indicated, particularly in the presence of abnormal extrathoracic FDG uptake, may represent an approach to reducing radiation exposure. However, this strategy should not currently be considered a replacement for routine whole-body CT in all patients; the potential diagnostic benefits and limitations of selective CT acquisition should be carefully considered on an individual basis.

Implementation of such a stepwise protocol could reduce CT-related radiation exposure, but may be associated with a modest increase in acquisition time and could affect workflow efficiency and patient throughput. Whether the potential reduction in radiation exposure outweighs the possible loss of clinically relevant information in individual patients requires further evaluation.

Therefore, our findings support consideration of individualized PET/CT protocols for appropriately selected patients rather than the routine omission of whole-body CT. Prospective and multicenter studies are needed to validate this approach and determine whether limiting CT coverage according to clinical indication and PET findings can maintain diagnostic performance and patient safety while providing a meaningful reduction in radiation exposure.

Ethics

Ethics Committee Approval: This study was conducted in accordance with the principles of the Declaration of Helsinki and was approved by the Ethics Committee of Gazi University Faculty of Medicine, Ankara (date: 14.12.2011, approval no: 362).

Informed Consent: Due to the retrospective nature of the study, the requirement for informed consent was waived.

Authorship Contributions

Concept: E.Ş.K., M.Ü., Design: E.Ş.K., Ü.Ö.A., M.Ü., Data Collection or Processing: E.Ş.K., Analysis or Interpretation: E.Ş.K., Ü.Ö.A., Literature Search: E.Ş.K., Writing: E.Ş.K.

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