DIAGNOSTIC YIELD OF ¹⁸F-FDG PET AFTER LUNG TRANSPLANTATION: A SINGLE-CENTER, RETROSPECTIVE COHORT STUDY

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Disclosures:

None of the authors of this manuscript have any conflicts of interest to disclose in relation with this manuscript. The authors confirm that that the work described has not been published previously, that it is not under consideration for publication elsewhere, that its publication is approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out, and that, if accepted, it will not be published elsewhere in the same form in English or in any other language, without the written consent of the copyright holder.

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions. All authors contributed in an important manner to the study design, data collection and analysis, or writing of the paper according to the guidelines of the International Committee of Medical Journal Editors (ICMJE). All authors have read and approved the manuscript, all authors take responsibility for the manuscript, and the submitting author has permission from all authors to submit the manuscript on their behalf.

Funding:

Following authors are supported by a research fellowship:

- RV is a senior clinical research fellow of the Fund for Scientific Research Flanders (FWO)
- OG and CMD are senior clinical investigators of the Fund for Scientific Research Flanders (FWO)
- GMV is supported by the Broere Charitable Foundation

MANUSCRIPT SUMMARY

Type: cohort study (single-center, retrospective, observational)

Take Home Message:

The diagnostic yield of ^{18}F -FDG PET for malignancy in lung transplant recipients is high.

Running title (34 characters): ^{18}F -FDG PET after lung transplantation

Key words: cancer, chronic lung allograft dysfunction, lung transplantation, malignancy, ^{18}F -FDG, PET, sensitivity, specificity

Word Count: Abstract: 190

Main body: 2529

References: 16

Figures: 2

Tables: 3

Online Supplemental Material: no

Reprint request: no reprints are requested

ABBREVIATIONS

bronchiolitis obliterans syndrome BOS

chronic lung allograft dysfunction CLAD

^{18}F -fluorodeoxyglucose-positron emission tomography ^{18}F -FDG PET

International Society for Heart and Lung Transplantation ISHLT

not otherwise specified NOS

post-transplant lymphoproliferative disorder PTL

restrictive allograft syndrome RAS

solid organ transplant SOT

ACCEPTED

Abstract

Background

To investigate the diagnostic yield of ^{18}F -fluorodeoxyglucose positron emission tomography (^{18}F -FDG PET) in lung transplant recipients.

Methods

A single-center, retrospective cohort study including 234 ^{18}F -FDG PET examinations in 199 lung transplant recipients. Indication for PET referral, ^{18}F -FDG PET diagnosis/findings and final clinical diagnosis were classified into three groups: malignancy, infection/inflammation not otherwise specified (NOS); and chronic lung allograft dysfunction (CLAD) with restrictive allograft syndrome (RAS) phenotype. Sensitivity/specificity analysis was performed to determine accuracy of ^{18}F -FDG PET in each group.

Results

Sensitivity of ^{18}F -FDG PET for malignancy was 91.4% (95% CI: 82.5-96.0%) and specificity was 82.3% (95% CI: 74.5-88.1%). Infection/inflammation NOS and RAS as indication for ^{18}F -FDG PET comprised relatively small groups (14 and 31 cases, respectively). In addition, ^{18}F -FDG PET revealed clinically relevant incidental findings in 15% of cases.

Conclusions

Referral for ^{18}F -FDG PET after lung transplantation mainly occurred to confirm or rule out malignancy. In this specific setting, ^{18}F -FDG PET has a high diagnostic yield. Accuracy of ^{18}F -FDG PET for other indications is less clear, given small sample sizes. Clinically relevant diagnoses, unrelated to the primary indication for ^{18}F -FDG PET, are found relatively often in this immunocompromised cohort.

INTRODUCTION

Patients who underwent lung transplantation (LTx) are at high risk for complications. Among these complications infection, “graft failure” and malignancy still remain an important source of morbidity and the leading cause of death¹. The most common cancer types after LTx - excluding skin tumours - are lung cancer and post-transplant lymphoproliferative disorder (PTLD), both most often localised inside the thorax².

¹⁸F-fluorodeoxyglucose-positron emission tomography (¹⁸F-FDG PET), often combined with simultaneous computed tomography (CT), is a non-invasive imaging tool increasingly used to diagnose and stage a variety of diseases. The ability of ¹⁸F-FDG PET to identify inflammatory/infectious or oncological sites is mainly related to glycolytic activity of cells involved in these disorders. Ample evidence exists on the usefulness of ¹⁸F-FDG PET in management of patients with lung cancer and infectious/inflammatory disorders in the general population^{3,4}. In addition, there is accumulating evidence on the value of ¹⁸F-FDG PET in patients with PTLD⁵.

The high level of immunosuppression after LTx and local factors after surgery, such as lymphatic remodelling and lack of bronchial artery re-anastomosis, however, may alter the LTx recipient's responses to infection or malignancy⁶. Theoretically, these changes could inversely affect local glucose metabolism, hence PET imaging results after LTx. Earlier studies have investigated the diagnostic yield of ¹⁸F-FDG PET for infectious or malignant complications in solid organ transplant (SOT) recipients^{7,8}. However, the number of LTx recipients in these studies was relatively small ($n \leq 31$ and $\leq 25\%$) and to our knowledge no large cohort study has been undertaken to determine the accuracy and clinical performance of ¹⁸F-FDG PET in LTx recipients.

Therefore, we conducted a large, retrospective study in our LTx cohort with the aim to determine the diagnostic yield of ¹⁸F-FDG PET for infectious/inflammatory or malignant complications in this specific population.

PATIENTS AND METHODS

Study design and patient selection

We conducted a single-center, retrospective cohort study including all LTx recipients who underwent ^{18}F -FDG PET from January 2008 until December 2015, during which period instrumentation and software for ^{18}F -FDG PET remained unchanged. Repeat ^{18}F -FDG PET in the same patient within 6 months of the previous ^{18}F -FDG PET performed for the same indication ('follow-up'), for example as a follow-up for PTLD, were excluded for analysis. Each new ^{18}F -FDG PET for a new clinical indication in the same patient was considered a new event for sensitivity/specificity analysis.

All LTx recipients had life-long, 3-4 monthly post-transplant follow-up at our institution. The local Ethics Committee approved the study and all patients had provided written informed consent at time of listing for LTx to access their clinical and biobanked data for research purposes (S51577). Demographic data, including ^{18}F -FDG PET results, clinical diagnosis, lung allograft function status and pathology reports were obtained from the patients' electronic medical records.

Positron Emission Tomography

^{18}F -FDG PET scans were performed on a PET stand-alone ECAT HR+ (Siemens, Knoxville, TN) or a PET/CT Biograph 40 TruePoint or Biograph 16 HiRez (both Siemens, Knoxville, TN). Patients fasted for at least 6 hours, had glucose levels below 180mg/dL at time of intravenous ^{18}F -FDG administration, and were given a nonselective beta-blocker (Propranolol 20mg) as per protocol. Acquisition was performed 60 minutes after ^{18}F -FDG administration. Whenever possible/available, whole-body CT scan (from skull to mid-thigh, either low-dose non-diagnostic or intravenously and orally contrast-enhanced diagnostic) was performed just prior to ^{18}F -FDG PET acquisition. PET emission images were corrected for scatter and attenuation based on concurrent CT information, if available. Scans were analyzed using a commercial software platform (Hybrid Viewer, Hermes Medical Solutions, Stockholm,

Sweden), final assessment and protocol finalization was performed by a skilled nuclear medicine physician (OG, CMD).

¹⁸F-FDG PET interpretation and reference standard

All ¹⁸F-FDG PET examinations were evaluated and rendered into a written report by experienced nuclear medicine physicians as part of routine clinical care. The clinical diagnosis made by the treating LTx physicians' team that was retained as the final diagnosis 6 months after ¹⁸F-FDG PET was used as reference standard. The clinical diagnosis was based on all available information, including clinical examination, laboratory results, histology, microbiology, imaging including ¹⁸F-FDG PET; and treatment outcome during follow-up during this 6-month period.

To allow for sensitivity/specificity analysis, primary indication for ¹⁸F-FDG PET referral, PET-based diagnosis and final clinical diagnosis were coded 2-dimensionally (0 = false, 1 = true) according to 3 categories: malignancy (including PTLT and all types of solid tumors), infection and/or inflammation not otherwise specified (NOS); and chronic lung allograft dysfunction (CLAD) with restrictive allograft syndrome (RAS) phenotype. Inflammation NOS was defined as an inflammatory response on ¹⁸F-FDG PET which could not be categorized into the other predefined groups (malignancy, infection, RAS); and could either include a more specific diagnosis (for example cryptogenic organizing pneumonia) or not. All data were collected by a trained general pulmonologist (WVR) and reviewed by a LTx pulmonologist (RV). An incidental finding (for example focal colonic uptake suspicious for a colon polyp) on ¹⁸F-FDG PET was not used in the primary sensitivity/specificity analysis, but used in a secondary analysis of incidental findings.

Statistical analysis

All analyses were performed using Graphpad Prism 8.0.2 (San Diego, CA, USA). Results are expressed as absolute values (percentage of total), mean ($\pm$ standard deviation) or median (interquartile range) wherever appropriate. Fisher's Exact or Chi Square test was used to

compare proportions and to calculate sensitivity/specificity. All p-values are two-tailed and $p < 0.05$ was considered statistically significant.

RESULTS

¹⁸F-FDG PET cohort

During the study period (2008-2015), a total of 329 ¹⁸F-FDG PET examinations were performed in 195 LTx recipients, of which 234 ¹⁸F-FDG PET were included in the current analysis, after exclusion of 95 (28.8%) repeat ¹⁸F-FDG PET (<6 month interval in same patient) (Figure 1).

Patient characteristics of the 234 individual ¹⁸F-FDG PET are summarized in table 1. Of the 195 included patients, 31 patients (15.6%) had more than one ¹⁸F-FDG PET performed: 23 patients (11.8%) had 2; and 8 patients (4.1%) had 3 ¹⁸F-FDG PET examinations, respectively. The majority of ¹⁸F-FDG PET examinations (178 out of 234, or 76.1%) were performed with simultaneous CT scan, allowing for subsequent attenuation correction and morphologic information. A total of 66 out of 234 (28%) ¹⁸F-FDG PET examinations were performed in diabetic patients, but per our institution's PET-protocol all patients had glucose levels below 180mg/dL at time of intravenous ¹⁸F-FDG administration.

Bilateral LTx procedure (74.4%), followed by single sided LTx (21.8%), heart-lung transplantation (2.6%) and combined lung-liver transplantation (1.3%) were included. Median age at time of transplantation was 56 (43-61) years; males (50.9%) and females (49.1%) were equally included. The most frequent indication for transplantation was emphysema (52.6%), followed by pulmonary fibrosis (23.9%), cystic fibrosis (CF) or non-CF bronchiectasis (16.2%), pulmonary hypertension (5.1%), or other diseases (2.1%), including obliterative bronchiolitis, lymphangioleiomyomatosis and epithelioid hemangioendothelioma.

Median time interval between ^{18}F -FDG PET and transplantation was 4.2 (1.6-7.9) years. Median follow-up time after transplantation at time of analysis was 8.3 (5.4-11.6) years. At time of analysis, 99 patients (50.7%) had died, which matches to deaths after 124 out of 234 (52.9%) ^{18}F -FDG PET examinations. CLAD diagnosis was made during follow-up in 111 out of 195 included patients (56.9%), with bronchiolitis obliterans syndrome (BOS) in 78 patients (70.3% of CLAD, or 40.0% of all patients) and RAS in 33 patients (29.7% of CLAD, or 16.9% of all patients), which equals CLAD diagnosis in 137 (BOS 96, RAS 41) out of 234 ^{18}F -FDG PET examinations (58.5%). CLAD diagnosis was made on average 8.7 months before time of ^{18}F -FDG PET examination.

The most important clinical indication for ^{18}F -FDG PET referral was malignancy (n=189, 80.8%), including i/ new lesions on chest X-ray or CT imaging during routine follow-up (n=71, 38%: parenchymal lesion(s) n=60, pleural lesion(s) n=7, adenopathy n=4), ii/ staging of documented malignancy (n=67, 35%: gastro-intestinal n=22, pulmonary n=15 (including n=1 in donor lung), neurologic n=9, ear-nose-throat n=6, hematologic n=5, urologic: n=5, skin n=4, gynecologic n=1, iii/ unexplained weight loss (n=50, 26%); and screening before retransplantation (n=1, 0.5%). ^{18}F -FDG PET was less frequently performed for infection/inflammation NOS (n=14, 6.0%: recurrent infections n=5, persistent inflammation n=5, unexplained pain n=1); and CLAD RAS, (n=31, 13.2%). In CLAD RAS, PET was performed for study purposes. Figure 2 shows representative images in these different pathologies, with either comparable or dissimilar regional ^{18}F -FDG PET appearance.

^{18}F -FDG PET diagnostic performance

Results of sensitivity/specificity analysis are summarized in table 2. Sensitivity for malignancy was 91.4% (95% confidence interval (CI) 82.5-96.0) and specificity was 82.3% (74.5-88.1). Positive predictive value (PPV) for malignancy was 75.3% (65.2-83.2) and negative predictive value (NPV) 94.2% (88.0-97.3). Accuracy was 85.7%.

Sensitivity, specificity, PPV, NPV and accuracy for infection/inflammation NOS was respectively 83.3% (55.2-97.0), 100% (17.8-100), 100% (72.3-100), 50% (8.9-91.1) and 85.7%; whereas for CLAD RAS this was respectively 78.6% (60.5-89.8), 33.3% (17.1-88.2), 91.7% (74.2-98.5), 14.3% (0.7-51.3) and 74.2%.

In infection/inflammation NOS, ^{18}F -FDG PET findings can be summarized as follows: negative/non-contributing (n=4), confirmation of known (and treated) pulmonary aspergillosis (n=3), new findings (n=7) including focal pneumonitis (culture negative, not treated) (n=3), aspergillus pleuritis (treatment started) (n=1), focal colitis (culture negative, not treated) (n=2) and granulomatous hepatitis *e causa ignota* (culture negative, not treated) (n=1).

Importantly, ^{18}F -FDG PET overall revealed clinically relevant incidental findings unrelated to the primary clinical indication for ^{18}F -FDG PET referral in 35 out of 234 cases (14.9%). These incidental diagnoses consisted of a broad range of diseases, summarized in table 3, of which malignancy and infection accounted for more than half of the findings.

DISCUSSION

As expected, the most important clinical indication for referral for ^{18}F -FDG PET after LTx was malignancy, consisting of more than 80% of all examinations in our study. The diagnostic yield of ^{18}F -FDG PET for malignancy, with a sensitivity of 91.4% and specificity of 82.4%, can be considered to be very good in this specific patient population. These results are comparable to earlier studies investigating ^{18}F -FDG PET in SOT recipients and only slightly lower compared to lung cancer staging in a more general patient cohort (with sensitivity up to 93% and specificity 96%)⁷⁻¹⁰. Due to its high sensitivity and NPV, ^{18}F -FDG PET can essentially be used as a 'rule-out' examination for malignancy in LTx recipients. However, when clinical suspicion remains very high in case of a (false) negative ^{18}F -FDG PET, other or more disease site-specific investigations should be pursued to come to a final diagnosis. In our patient cohort, for instance, of the 6 patients with a false negative ^{18}F -FDG PET 3 patients were diagnosed with PTLD (brain, colon and epiglottis), 1 patient with non-small cell lung cancer, 1 patient

with Ewing sarcoma (an entity which can have low ^{18}F -FDG avidity) and 1 patient with transitional cell carcinoma of the bladder (for which sensitivity is very low due to urinary ^{18}F -FDG excretion). The slightly lower PPV for malignancy (75%) is most likely caused by the relatively high prevalence of infective/inflammatory diseases that are found in this highly immunocompromised patient group.

In contrast to malignancy, infection/inflammation NOS was far less the referral indication for ^{18}F -FDG PET, resulting in low patient numbers for these conditions. Therefore, no firm conclusions can be made regarding the diagnostic accuracy of ^{18}F -FDG PET in these conditions. Nevertheless, given the high diagnostic yield of ^{18}F -FDG PET for malignancy in the current study and its usefulness for infectious/inflammatory diseases in the general population, it is reasonable to assume that ^{18}F -FDG PET has similar added value for diagnosing infectious/inflammatory disorders in this immunocompromised patient population, as demonstrated by the relatively high prevalence of inflammatory findings (pneumonitis, pleuritis, colitis, hepatitis) in this subgroup of our study, but this warrants further investigation⁴. Interestingly, preclinical studies in an orthotopic LTx mouse model demonstrated increased glucose uptake in CD8^+ T-cells during acute lung graft rejection¹¹. However, in a clinical study of LTx recipients, increased ^{18}F -FDG-uptake was only present in proven infection, but no abnormal uptake was observed in the absence of infection or sole presence of acute cellular rejection¹², possibly suggesting that ^{18}F -FDG PET may discriminate between infection and acute cellular rejection after LTx. Yet, acute cellular rejection is characterised by high levels of activated T-lymphocytes, specifically binding interleukin (IL)-2 to high-affinity IL-2 receptors on the cell membrane. Therefore, nuclear imaging with $^{99\text{m}}\text{Tc}$ -HYNIC-IL-2 or ^{18}F -IL-2 may perhaps be more suited and specific to detect acute cellular rejection after LTx¹³.

Next to the retrospective design of the current study, our smaller sample size also prohibits to make firm conclusions regarding possible prospective utility of ^{18}F -FDG PET as diagnostic tool in CLAD RAS. In RAS patients, PET was performed for study purposes to assess discernment of RAS from BOS by specific imaging and to have an idea about the maximum Standardized Uptake Value (SUVmax) of the persistent parenchymal opacities. Indeed, we have previously demonstrated the value of ^{18}F -FDG PET to retrospectively distinguish CLAD phenotypes and stable LTx recipients by using SUVmax, which was mainly increased in intrapulmonary and subpleural fibrotic areas in RAS, allowing to discriminate RAS from BOS with 76% sensitivity and 87% specificity¹⁴ and which may be of prognostic¹⁴ and/or therapeutic¹⁵ importance in RAS. In the current study, however, the broad confidence interval of both sensitivity and specificity indicates that ^{18}F -FDG PET alone is insufficient to discriminate RAS from malignancy or infection/inflammation, which reflects the importance of the clinical context in diagnosing each condition. Of particular note is the relatively high prevalence of incidental findings (up to 15%) on ^{18}F -FDG PET in this immunocompromised patient cohort. Therefore, as a general rule, appropriate attention for secondary findings on ^{18}F -FDG PET is advisable in this specific population.

Limitations of our study are inherent to its single center, retrospective design, with rather limited patient numbers and a large study-period over several decades, during which different prophylactic and therapeutic strategies may have been applied. In addition, there has been a technical evolution in PET cameras and the introduction of hybrid PET-CT technology, which is known to enhance diagnostic accuracy compared to PET alone. Also, clinical differential diagnosis between different pathologies may sometimes be difficult, such as for instance respiratory infection, organising pneumonia or malignancy, yet the currently used time interval of 6 months following ^{18}F -FDG PET and assessment of all medical tests and treatments during this time interval by experienced clinicians in order to obtain a final diagnosis for sensitivity/specificity-analyses, significantly decreases the chance of misclassification and

possible bias. Moreover, no ^{18}F -FDG PET was performed during the first month after transplantation in our study, thus excluding non-specific early post-operative inflammation or ischemia-reperfusion-injury/primary graft dysfunction as possible reasons for the observed increase in pulmonary ^{18}F -FDG uptake in our cohort¹⁶. Finally, specific assessment of PET-performance according to nodule size ($> < 10$ mm), number of pulmonary nodules, or composition (ground-glass, solid) in the 60 patients with documented parenchymal lesions on chest X-ray or CT imaging during standard follow-up which instigated PET subsequent PET examination, was not possible as this was outside the initial scope of the paper.

In conclusion, the current largest single-center study confirms the use of ^{18}F -FDG PET as an excellent diagnostic tool for malignancy in LTx recipients. Firm conclusions concerning other conditions could not be made from this study. However, based on previous data on ^{18}F -FDG PET in other cohorts, it is reasonable to assume that ^{18}F -FDG PET may also have added value for detecting infection, inflammation and CLAD RAS. The high prevalence of incidental findings on ^{18}F -FDG PET warrants for extra attention when assessing ^{18}F -FDG PET in LTx recipients.

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FIGURES

Figure 1: Flow chart of lung transplant recipient and ^{18}F -FDG PET inclusion

Figure 2: Comparison of ^{18}F -FDG PET for various indications after lung transplantation

Figure 2 Legend:

Representative images of lung transplant recipients undergoing ^{18}F -FDG PET demonstrating comparable or dissimilar regional findings between the various indications/diagnosis (malignancy, infection, RAS), all PET images were scaled to the same standardized uptake value (SUV 0 -7).

TABLES

Table 1: Characteristics of 234 ^{18}F -FDG PET in 195 lung transplant recipients

	^{18}F -FDG PET (n=234)	
Type of ^{18}F-FDG PET, n (%)		
with CT	178	(76.1%)
without CT	56	(23.9%)
Type of lung transplantation, n (%)		
Bilateral lung	174	(74.4%)
Single lung	51	(21.8%)
Heart-lung	6	(2.6%)
Combined lung-liver	3	(1.3%)
Sex, n (%)		
Male	119	(50.9%)
Female	115	(49.1%)
Underlying disease, n (%)		
Emphysema (including alfa1-antitrypsin deficiency)	123	(52.6%)
Pulmonary fibrosis	56	(23.9%)
CF and non-CF bronchiectasis	38	(16.2%)
Pulmonary hypertension (primary or Eisenmenger)	12	(5.1%)
Other (including OB, LAM, EHE)	5	(2.1%)
Age at transplantation, y	56	(43-61)
CLAD at time of analysis, n (%)	137	(58.5%)
Bronchiolitis obliterans syndrome	96	(41.0%)
Restrictive allograft syndrome	41	(17.5%)
Time interval between CLAD diagnosis and PET, d	-267	(-1087 - 382)
Time interval between transplantation and PET, y	4.2	(1.6-7.7)
Time of follow up at time of analysis, y	8.3	(5.4-11.6)

Table 1 legend:

CF= cystic fibrosis, CLAD = chronic lung allograft dysfunction CT= computed tomography, EHE = epithelioid hemangioendothelioma, LAM = lymphangioleiomyomatosis, OB = obliterative bronchiolitis

Table 2: Diagnostic accuracy of ^{18}F -FDG PET after lung transplantation**A. Main sensitivity/specificity analysis**

	Infection/inflammation		
	Malignancy	NOS	RAS
Indication for PET (n)	189	14	31
positive PET	85	10	24
positive PET +Clin	64	10	22
positive PET -Clin	21	0	2
negative PET	104	4	7
negative PET +Clin	6	2	6
negative PET -Clin	98	2	1
PET other indication	45	220	203
positive PET	1	73	3
positive PET +Clin	0	53	3
positive PET -Clin	1	20	0
negative PET	44	147	200
negative PET +Clin	0	15	1
negative PET -Clin	44	132	199
Total	234	234	234

B. Malignancy

Malignancy, n	Clin positive	Clin negative	
PET positive	64	21	TP+FP 85
PET negative	6	98	FN+TN 104
	TP+FN	FP+TN	
	70	119	

Effect size	Value	95% CI
Sensitivity	0.9143	0.8253 to 0.9601
Specificity	0.8235	0.7452 to 0.8816
PPV	0.7529	0.6517 to 0.8324
NPV	0.9423	0.8798 to 0.9733
Accuracy	0.8571	

C. Infection/Inflammation NOS

Infection/inflammation, n	Clin positive	Clin negative	
PET positive	10	0	TP+FP 10
PET negative	2	2	FN+TN 4
	TP+FN	FP+TN	
	12	2	

Effect size	Value	95% CI
Sensitivity	0.8333	0.5520 to 0.9704
Specificity	1	0.1777 to 1.000
PPV	1	0.7225 to 1.000
NPV	0.5	0.08884 to 0.9112
Accuracy	0.8571	

D. CLAD RAS

RAS, n	Clin positive	Clin negative		
PET positive	22	2	TP+FP	24
PET negative	6	1	FN+TN	7
	TP+FN	FP+TN		
	28	3		

Effect size	Value	95% CI
Sensitivity	0.7857	0.6046 to 0.8979
Specificity	0.3333	0.01710 to 0.8815
PPV	0.9167	0.7415 to 0.9852
		0.007328 to
NPV	0.1429	0.5131
Accuracy	0.7419	

Table 2 legend:

PPV: positive predictive value. NPV: negative predictive value. Clin: clinical diagnosis (reference standard 6 months after ^{18}F -FDG PET). TP: true positive. TN: true negative. FP: false positive. FN: false negative. CLAD RAS: chronic lung allograft dysfunction, restrictive allograft syndrome phenotype.

Table 3: Clinically relevant incidental findings on 234 ^{18}F -FDG PET in 195 lung transplant recipients

Incidental finding	Number	Subtype
Hyperplastic thyroid nodule	2	END
Multinodular goiter	1	END
Oesophagitis	1	GI
Small intestine invagination	1	GI
Colon polyp	4	GI
Cholecystitis	1	GI
Ovarian cyst	1	GYN
Sinusitis	1	RESP
Pneumonia	8	RESP
Bronchiolitis/BOOP	2	RESP
Pleuritis	2	RESP
CLAD RAS	1	RESP
Pulmonary embolism w infarction	1	RESP
Warthin's tumor	3	ONC
Lung cancer	1	ONC
Metastatic colon cancer	1	ONC
Peri-prosthetic inflammation	1	ORT
Bursitis trochanterica	1	ORT
Avascular necrosis	2	ORT
Total	35 (14.9%)	

Table 3 legend:

Incidental findings on ^{18}F -FDG PET were detected unrelated to the primary clinical indication for ^{18}F -FDG PET referral and confirmed by concurrent CT scan or other diagnostic investigations during follow-up after ^{18}F -FDG PET. END: endocrine, GI: gastro-intestinal, GYN: gynaecologic, RESP: respiratory, ONC: oncologic, ORT: orthopaedic.

Figure 1

Figure 2

Comparable regional ^{18}F -FDG PET appearance

Dissimilar regional ^{18}F -FDG PET appearance