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Pancreatic Fat Is Associated With Metabolic Syndrome and Visceral Fat but Not Beta-Cell Function or Body Mass Index in Pediatric Obesity

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Objective: Adolescents with obesity have increased risk of type 2 diabetes and metabolic syndrome (MetS). Pancreatic fat has been related to these conditions; however, little is known about associations in pediatric obesity. The present study was designed to explore these associations further.

Methods: We examined 116 subjects, 90 with obesity. Anthropometry, MetS, blood samples, and oral glucose tolerance tests were assessed using standard techniques. Pancreatic fat fraction (PFF) and other fat depots were quantified using magnetic resonance imaging.

Results: The PFF was elevated in subjects with obesity. No association between PFF and body mass index-standard deviation score (BMI-SDS) was found in the obesity subcohort. Pancreatic fat fraction correlated to Insulin Secretion Sensitivity Index-2 and Homeostatic Model Assessment of Insulin Resistance in simple regression; however, when using adjusted regression and correcting for BMI-SDS and other fat compartments, PFF correlated only to visceral adipose tissue and fasting glucose. Highest levels of PFF were found in subjects with obesity and MetS.

Conclusions: In adolescents with obesity, PFF is elevated and associated to MetS, fasting glucose, and visceral adipose tissue but not to beta-cell function, glucose tolerance, or BMI-SDS. This study demonstrates that conclusions regarding PFF and its associations depend on the body mass features of the cohort.

Key Words: pancreatic fat, pediatric obesity, beta-cell function, metabolic syndrome, body mass index-standard deviation score

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The prevalence of pediatric obesity and type 2 diabetes mellitus has increased in recent decades.[1,2] Obesity-related metabolic complications are associated with distribution and amount of lipids stored in adipose tissue compartments.[3] Accumulation of lipids in subcutaneous adipose tissue (SAT) is complemented with storage in visceral adipose tissue (VAT) and other ectopic sites such as the liver and pancreas.[3] Pancreatic fat fraction (PFF) can be measured by magnetic resonance imaging (MRI) and increase with body mass index (BMI) both in adults[4] and adolescents.[5,6] In addition, elevated PFF has been associated with age, male sex, and Hispanic ethnicity.[7,8]

Pancreatic fat is located in close proximity to insulin-secreting beta-cells and is a part of the total ectopic fat deposition, which implies that it could potentially be associated to both beta-cell function (BCF) and insulin resistance (IR). Indeed, pancreatic fat has been connected to impaired BCF in both adults[4,9] and youth.[10] In contrast, other previous studies have found no such relationship.[5–8,11] Furthermore, several studies report associations between high PFF and IR as well as impaired glucose metabolism.[6,9,10,12] A gradual increase in PFF between subjects with normal glucose tolerance (NGT), impaired fasting glucose (IFG), and impaired glucose tolerance (IGT) has been demonstrated.[13] The highest levels of PFF have been found in subjects with diabetes.[9,14]

The prevalence of MetS in adults has been estimated at approximately 20% to 30% and at 12% to 30% in adolescents.[2,15,16] In addition, elevated levels of PFF have been linked to MetS in both adults[12,17] and adolescents.[5] Furthermore, disturbed levels of proinsulin as well as the proinsulin-to-insulin (P/I) ratio have been proposed as possible biomarkers of beta-cell dysfunction and impaired glucose regulation. These biomarkers have also been

associated to MetS[18,19]; however, their relation to PFF has yet not been studied.

This study had 4 main objectives. These were to carefully measure PFF in children and adolescents with and without obesity and to 1. relate it to indices of BCF and IR; 2. explore a previously reported correlation between PFF and MetS; 3. examine whether PFF differs between subjects with NGT and IFG/IGT; and 4. study the correlation between PFF and other body composition measurements including MRI-based quantification of VAT, SAT, and liver fat fraction (LFF) and BMI-standard deviation score (SDS). The results and discussion sections are structured to follow the order of these objectives.

MATERIALS AND METHODS

Study Population

This dual-center cross-sectional study was carried out at Uppsala University Hospital, Sweden and Paracelsus Medical University Hospital in Salzburg, Austria. Children and adolescents (N = 125) aged 10 to 18 years and part of the beta-JUDO (beta-cell function in JUvenile Diabetes and Obesity) cohort (FP7-HEALTH-2011-two-stage, project number: 279153) were included based on age. Subjects unable to comply with the MRI and oral glucose tolerance test (OGTT) protocols were excluded. Furthermore, 9 subjects were excluded because of missing PFF or OGTT datasets, leaving 116 subjects with complete datasets to be further analyzed. Ninety (44 females) subjects were characterized with obesity (BMI-SDS ≥ 2.0) and 26 (12 females) as nonobese (BMI-SDS < 2.0).[20,21] The latter group is not denoted *controls* because it includes both overweight and underweight subjects. Examinations were harmonized between study centers. Written parental and oral consent from children as well as ethical approval from local ethics committees were obtained.

Anthropometric and Blood Pressure Measurements

Height and weight were assessed by standardized and calibrated scales (Seca, Hamburg, Germany) and stadiometers (Uppsala: Ulmer (Busse design); Salzburg: Seca). The BMI-SDS was calculated with Microsoft Excel add-in LMS Growth using WHO growth report.[21] Waist circumference was measured midway between the superior border of the iliac crest and lowest rib. Systemic blood pressure was measured using a standardized clinical aneroid sphygmomanometer (Uppsala: CAS 740; CAS Medical Systems, Inc, Branford, Conn; Salzburg: Carescape V100; Dinamap Technology/GE, Vienna, Austria).

Blood Sampling and Analyses

Blood was sampled at fasting using an intravenous stationary catheter. Glucose, triacylglycerides (TG) and high-density lipoproteins (HDL) were analyzed according to local protocols. In Uppsala, glucose was analyzed using an Architect c8000 instrument (Abbott Diagnostics, Solna, Sweden) and by a Glucoquant Glucose-Kit (Roche Diagnostics, Mannheim, Germany) in Salzburg. Uppsala quantified TG and HDL using an Architect c800 instrument (Abbott Diagnostics) and in Salzburg an enzymatic photometric test (Modular Analytics System, P-Modul, 917; Roche Diagnostics) was used. Validation of analyses was performed between the laboratories in Uppsala and Salzburg using reference blood samples.

Selected samples underwent immediate centrifugation at 2500*g* for 10 minutes at 4°C, subsequently aliquoted, and frozen at −80°C. Plasma was later used for central analyses of insulin, proinsulin, and C-peptide in Uppsala. Single-plex enzyme-linked immunosorbent assay kits for each analyte were used (Mercodia AB, Uppsala, Sweden). Standardized control samples (Mercodia AB) were used to control for interplate variability.

Oral Glucose Tolerance Test

The OGTTs were conducted as previously described.[22] Subjects were instructed to drink a 300-mL glucose solution (1.75 g glucose per kilogram body weight; maximum 75 g glucose) within approximately 5 minutes. Subsequently, blood samples were obtained from a stationary venous catheter at predetermined time points after the glucose challenge.

Definition of Metabolic Syndrome and Prediabetes

The MetS was defined according to the International Diabetes Federation consensus for children and adolescents.[23] Prediabetes was defined as IFG and/or IGT according to the American Diabetes Association[24] because of the same fasting glucose cutoff level (≥5.6 mmol) as in MetS.

Beta-cell function and IR

To estimate BCF and IR, several indices were used. Homeostatic model assessment (HOMA)-beta and P/I were derived from fasting measurements.[25,26] First-phase insulin secretion during OGTT was evaluated by insulinogenic index (IGI) using 15 and 30 minutes as well as both insulin and C-peptide in the numerator.[27] The area under the curve (AUC), calculated using the trapezoid rule, for glucose, insulin, and C-peptide was used to represent both total and dynamic secretory response for the entire OGTT period. Dynamic AUC was calcuted as the AUC above baseline (t=0). The BCF corrected for insulin sensitivity was assessed by the oral disposition index (IGI × Matsuda index) and the insulin secretion sensitivity index-2 (ISSI-2) ([AUCinsulin/AUCglucose] × Matsuda index).[10,26] The IR was assessed by HOMA-IR, 1/fasting insulin, and by the Matsuda index.[26,28]

Magnetic Resonance Imaging

The MRI examinations were performed to determine PFF, LFF, and volumes of abdominal VAT and SAT. All examinations were performed using 1.5 Tesla clinical MRI systems from Philips Medical System (Best, The Netherlands). Uppsala used a Philips Achieva system, whereas Salzburg used a Philips Ingenia system. Uppsala served as core laboratory and developed and standardized the imaging protocol at both sites and performed all image analyses.

Imaging was conducted in a supine position after a standardized light meal in proximity to the OGTT, preferably on the same day. All MRI assessments used water-fat imaging techniques during breath hold. The pancreas scan was performed using surface coils, and the LFF and VAT/SAT scans were performed using the built-in body coils. The pancreas scan was tilted (−15 degrees around the coronal direction) for better pancreas coverage.

For both pancreas and liver, the water-fat image reconstruction was performed using a multiresolution version of a previously described method that uses a whole-image optimization approach.[29] The reconstruction used the same TG spectrum model,[30] a common R2* parameter, and a regularization parameter ($\mu = 10$). The water and fat image reconstruction was performed using the last 5 echoes only because phase errors in the first echo were seen to significantly affect the results.[31,32] The first and last slices in each volume were excluded from the analysis because the image contrast in these slices differed.

An experienced operator performed the measurements using manual segmentation. The segmentations were performed in the

water images using the software ImageJ (version 1.42q, http://rsbweb.nih.gov/ij/). To reduce the effect of partial volume between the pancreas and surrounding adipose tissue, the pancreas boundary was avoided, and the median fat fraction value in each segmented volume of interest was used. For improved precision, 1 operator segmented each pancreas twice with approximately 1 month in between measurements. The averages of the 2 fat fraction measurements were used as final estimate of PFF. Repeated measurements of the whole cohort gave significantly different mean values of 3.11% and 2.88% ($P = 0.02$). The SD between the repeated measurements was on average 0.54 percentage points. Details on examination of LFF, SAT, and VAT can be found in the Supplemental Digital Content, Appendices A and B, http://links.lww.com/MPA/A565.

Statistical Analyses

Data are presented as median and range or mean ± SD depending on data distribution. Screening for normality was done by Shapiro-Wilk test. Most parameters were not normally distributed, therefore nonparametric tests were applied: the Spearman rank test (correlations) and Mann-Whitney *U* test (group differences). Normally distributed data were analyzed based on parametric tests: the Student *t* test (group differences).

Significant associations were further analyzed using adjusted regression models, controlling for age and body composition. The PFF was logarithm-transformed and 2 models were used. The first (model A) included age and BMI-SDS. The second (model B) included VAT, SAT, and LFF. Only parameters that were significantly associated to PFF in simple regression, in the respective subcohorts, were used as covariates in the 2 models. The association between PFF and MetS was controlled for by VAT using analysis of covariance. All statistical procedures were determined before the analyses started. Statistical analyses were performed using GraphPad Prism 6.0c (GraphPad Software Inc, La Jolla, Calif) and Statistica 12 (Statsoft Inc, Tulsa, Okla). The level of significance was $P < 0.05$.

RESULTS

Basic Characteristics

Characteristics of study subjects are presented in Table 1. Associations between PFF and other parameters are presented in Table 2, with separate analyses performed for the whole cohort as well as the subcohorts (subjects with and without obesity, respectively). Age and sex ratios did not differ between the subcohorts. Age, BMI-SDS, and PFF did not differ between sexes. All fat compartments measured were significantly higher in subjects with obesity (Table 1). The PFF was not related to age in this cohort (Table 2).

Pancreatic Fat Fraction and BCF

Fasting insulin, proinsulin, and C-peptide levels were significantly elevated in subjects with obesity (Table 1). In the whole cohort, these parameters were positively correlated to PFF in simple regression models; however, all correlations except fasting C-peptide lost significances in subjects with obesity (Table 2). Although the association between ISSI-2 and PFF was negative, a positive correlation was found regarding $AUC_{proinsulin}$ in the whole study group. The ISSI-2 was also significantly correlated to PFF in subjects with obesity; however, significance was lost in adjusted regression analysis (Table 2). Regarding other parameters of insulin secretion and BCF, no associations were found.

Pancreatic Fat Fraction and IR

Subjects with obesity had higher IR than nonobese subjects (Table 1). Furthermore, IR calculated by Matsuda index, HOMA-IR, and 1/fasting insulin were all associated to PFF in the whole cohort (Table 2). When only obese individuals were examined, a significant relationship between HOMA-IR and PFF was found in the simple regression model (Table 2), but no significant correlations were found in adjusted regression models.

Pancreatic Fat Fraction and MetS

To investigate association between PFF and MetS, the study population was divided into 3 groups: subjects without obesity (group 1), subjects with obesity but without MetS (group 2), and subjects with obesity and MetS (group 3). The groups did not differ with regard to age or sex, and groups 2 and 3 did not differ with regard to BMI-SDS (data not shown). As depicted in Figure 1, a gradual increase in PFF was shown between groups. Group 1 (n = 26): 1.05 (−0.4–3.3)%; group 2 (n = 66): 2.2 (−0.6–11.8)%; and group 3 (n = 24): 3.65 (1.2–14.6)% (1 vs 2: $P = 0.002$; 2 vs 3: $P = 0.016$). In group 3, IR, fasting insulin, and proinsulin levels were also significantly elevated (data not shown). Systolic blood pressure and triglyceride levels were elevated in subjects with obesity, whereas no difference in HDL or fasting glucose levels was detected between subjects with and without obesity (Table 1). After adjustment for VAT, the association of PFF and MetS had a *P* value of 0.051 between the groups with obesity and 0.058 between all groups.

Pancreatic Fat Fraction and Glucose Metabolism

Fasting glucose was associated with PFF in subjects with obesity (Table 2). Subjects with IFG had higher PFF compared with subjects with NGT (3.4% vs 2.2%, $P = 0.026$). Moreover, a trend was observed between PFF and the 2-hour glucose level in obese children (Table 2). The PFF did, however, not differ between obese NGT and obese prediabetic subjects (IFG and IGT) ($P = 0.105$), and no difference was detected between obese IFG and IGT ($P = 0.276$). In subjects without obesity, a negative correlation between PFF and fasting glucose was observed (Table 2). When adjusted regression modeling was used, only PFF and fasting glucose in subjects with obesity remained significantly correlated (r = 0.243, $P = 0.020$).

Pancreatic Fat Fraction, Other Fat Compartments, and BMI-SDS

In the whole cohort, PFF was positively correlated to VAT, SAT, and liver fat (Table 2). However, VAT was the only significant parameter in adjusted models (model A: r = 0.289, $P = 0.021$; model B: r = 0.340, $P = 0.027$). In addition, when subjects with obesity were examined, only VAT showed correlation to PFF in simple regression models. When examining ectopic fat deposition in the pancreas and liver, a positive correlation was found in subjects without obesity. In subjects with obesity, no association was found (Table 2) (Fig. 2). The BMI-SDS correlated to amount of PFF in the whole cohort and in subjects without obesity; however, no correlation between BMI-SDS and PFF in subjects with obesity was found (Table 2) (Fig. 3).

Cohort-Dependent Results

Associations between PFF and other parameters were frequently found dependent on the cohort examined (Table 2). Comparing the whole cohort with the obesity subcohort, 12 associations to PFF were differently correlated. These differences were found

TABLE 1. Descriptive Data and Group Comparison Between Children and Adolescents Without Obesity (Nonobese) and With Obesity (Obese)

	Nonobese, n = 26	Obese, n = 90
Females, n (%)	12 (46%)	44 (49%)
Age, y	13.8 ± 1.9	14.1 ± 2.2
BMI-SDS	0.68 ± 1.2	3.0 ± 0.5*
Fat distribution		
Pancreatic fat fraction, %	1.1 (−0.4–7.1)	2.4 (−0.6–14.6)†
VAT, cm^3	558.0 (99.0–1718.4)	1413.0 (796.2–3842.5)*
SAT, cm^3	1753.0 (170.3–6861.7)	6905.0 (2910.0–12,393.0)*
Liver fat fraction, %	1.6 (0.6–49.9)	5.8 (1.3–45.6)*
Beta-cell function		
Fasting insulin, pmol/L	50.1 (8.7–213.4)	119.3 (32.2–392.3)*
Fasting proinsulin, pmol/L	7.3 (2.7–19.9)	19.8 (2.7–73.0)*
Fasting C-peptide, pmol/L	482.6 (105.1–1189.0)	815.6 (331.0–2089.0)*
HOMA-beta	88.5 (22.8–482.7)	227.8 (40.8–1134.9)*
IGI 30 min (insulin)	25.4 (3.6–95.1)	41.3 (8.3–157.9)‡
oDI	2638.5 (833.8–7831.4)‡	1735.5 (308.7–9003.5)
Insulin sensitivity		
HOMA-IR	1.7 (0.3–6.5)	4.0 (0.9–15.0)*
Matsuda index	94.5 (37.6–459.5)*	42.9 (10.1–139.0)
MetS, n (%)	0	24 (27%)
Blood pressure		
SBP, mm Hg	112.2 ± 7.0	122.2 ± 11.5†
DBP, mm Hg	67.4 ± 6.2	68.0 ± 10.6
Lipid metabolism		
TG, mmol/L	0.6 (0.4–1.2)	1.1 (0.4–4.5)*
HDL-C, mmol/L	1.3 (1.0–2.8)	1.2 (0.7–2.5)
Glucose metabolism		
IGT, n (%)	2 (8%)	17 (19%)
IFG, n (%)	6 (23%)	10 (11%)
Fasting glucose, mmol/L	5.1 ± 0.6	5.0 ± 0.7

Values are mean ± SD or median (range).

*$P < 0.0001$.

†$P < 0.001$.

‡$P < 0.01$.

DBP indicates diastolic blood pressure; HDL-C, high-density lipoprotein cholesterol; oDI, oral disposition index; and SBP, systolic blood pressure.

within all areas examined: BMI-SDS, BCF, IR, MetS components, glucose metabolism, and fat compartments (Table 2).

DISCUSSION

Fat accumulation in the pancreas could potentially have an effect on insulin-producing beta-cells, both directly through lipotoxicity mediated by the release of free fatty acids and indirectly through activation of inflammatory pathways.[7] Indeed, PFF has been shown to correlate with pancreatic TG content[33] and circulating free fatty acids.[7] However, whether pancreatic adipocyte infiltration reflects intra-islet fat content and whether adipose tissue within the pancreas has a profound effect on insulin-secreting beta-cells remain unclear.[10] When we in this study compared pediatric subjects with and without obesity, significant differences could be found in PFF as well as in parameters of BCF and IR (Table 1). However, when simple regression analyses were performed, only few parameters of BCF showed an association to PFF (Table 2). The ISSI-2 correlated to PFF in subjects with obesity, confirming previous results in youth.[10] Cohen et al[10] investigated BCF and IR in juveniles with *PFF absent* and *PFF present*, respectively. The PFF-present group had impaired BCF and elevated IR[10]; however, only 29% of the subjects were found in this group, which must be considered when interpreting the results. Indeed, Cohen et al[10] showed a relation between PFF and ISSI-2 in a group comparison, but when adjusting for BMI-SDS and VAT, no correlation between PFF and any indices of BCF remained significant in this study. This also agrees with recently published data in adults.[11] These previous findings and our concurring data lead us to conclude that PFF is not directly associated to BCF in childhood.

Interestingly, PFF correlated to fasting proinsulin and $AUC_{proinsulin}$ in the whole cohort, indicating that elevated PFF could potentially contribute to beta-cell stress and disturbed intracellular insulin processing. Proinsulin has previously been related to beta-cell dysfunction.[18] However, when analyzing subcohorts separately, no correlations remained indicating that the positive correlations may be due to group differences. In addition, in the whole cohort, PFF was related to IR verifying previous results of ectopic fat relating to IR.[9,10,12] Nonetheless, in obese children,

TABLE 2. Simple Spearman Rank Correlations Between Pancreatic fat fraction and Phenotype Data

	Pancreatic fat fraction					
	Whole Study Group (n = 116)		Obese (n = 90)		Nonobese (n = 26)	
	Simple Regression					
	$r_{Spearman}$	*P*	$r_{Spearman}$	*P*	$r_{Spearman}$	*P*
Age	−0.059	0.526	−0.074	0.486	−0.181	0.377
BMI-SDS	**0.276**	**0.003**	0.021	0.841	**0.399**	**0.043**
Beta-cell function						
IGI 15 min_{OGTT} insulin	0.091	0.345	0.016	0.884	−0.118	0.600
IGI 30 min_{OGTT} insulin	0.106	0.266	0.017	0.875	0.013	0.951
IGI 15 min_{OGTT} c-peptide	0.056	0.564	−0.023	0.854	−0.076	0.737
IGI 30 min_{OGTT} c-peptide	0.038	0.691	−0.046	0.670	0.087	0.672
HOMA-beta	0.183	0.053	−0.004	0.969	0.177	0.397
oDI	−0.126	0.194	−0.133	0.232	0.278	0.178
ISSI-2	**−0.242**	**0.012**	**−0.301**	**0.006**	0.311	0.131
AUC insulin	0.177	0.057	0.074	0.490	−0.211	0.302
AUC proinsulin	**0.183**	**0.050**	0.094	0.378	−0.278	0.169
AUC c-peptide	0.170	0.068	0.063	0.555	−0.134	0.516
Dynamic AUC insulin	0.159	0.088	0.050	0.639	−0.159	0.439
Dynamic AUC proinsulin	0.157	0.093	0.076	0.475	−0.288	0.153
Dynamic AUC c-peptide	0.098	0.296	−0.020	0.852	−0.097	0.639
P/I fasting	−0.022	0.814	−0.062	0.561	−0.035	0.866
P/I 15 min_{OGTT}	0.092	0.328	0.074	0.489	−0.173	0.409
P/I 30 min_{OGTT}	−0.052	0.577	−0.056	0.602	−0.227	0.265
Insulin sensitivity						
HOMA-IR	**0.284**	**0.002**	**0.211**	**0.047**	−0.219	0.282
Matsuda index	**−0.271**	**0.005**	−0.210	0.057	0.260	0.209
1/Insulin	**−0.268**	**0.004**	−0.179	0.091	0.116	0.574
MetS components						
Waist circumference	**0.312**	**0.001**	0.108	0.327	0.308	0.127
Systolic blood pressure	**0.210**	**0.026**	0.037	0.734	0.279	0.168
Diastolic blood pressure	0.124	0.191	0.150	0.168	0.008	0.968
Triglycerides	**0.193**	**0.038**	0.019	0.860	0.098	0.632
HDL	−0.122	0.196	−0.173	0.105	0.209	0.316
Fasting glucose	0.107	0.257	**0.290**	**0.006**†	**−0.527**	**0.006**
Glucose metabolism						
Glucose 120 min	0.155	0.099	0.166	0.120	−0.088	0.675
Fasting insulin	**0.268**	**0.004**	0.179	0.092	−0.114	0.578
Fasting proinsulin	**0.237**	**0.011**	0.131	0.218	−0.202	0.324
Fasting C-peptide	**0.325**	**<0.001**	**0.223**	**0.035**	0.100	0.627
Fat compartments						
VAT	**0.414**	**<0.001*†**	**0.223**	**0.034**	**0.472**	**0.015**
SAT	**0.272**	**0.003**	0.041	0.701	0.294	0.145
Liver fat	**0.273**	**0.003**	0.033	0.758	**0.480**	**0.013**

Bold letters indicate significant univariate correlations.

*†Significant results after controlling for significant covariates using models A and B, respectively. Model A includes age and BMI-SDS and model B includes VAT, SAT, and liver fat.

only HOMA-IR remains significant, and in adjusted regression models, no significant correlations were found (Table 2). Therefore, we conclude that PFF is not a marker of proinsulin secretion or the result of IR in adolescence. Other depots such as visceral fat and hepatic fat are likely to be more strongly associated to IR.[6]

Obesity is associated with increased risk of MetS.[34] In the present study, PFF was significantly higher in subjects with obesity and MetS, confirming previous studies both in adults[12] and adolescents.[5] However, Lee et al[12] used computed tomography to quantify PFF in adults, whereas Maggio et al[5] included only 5 adolescents with MetS. We found that both PFF and VAT were elevated in subjects with obesity and MetS and related to each other. The PFF was not independently associated to MetS when adjusting for VAT ($P = 0.051$), indicating that VAT constitutes a link. On the other hand, we acknowledge a very strong trend between PFF and MetS, independently of VAT, that challenges

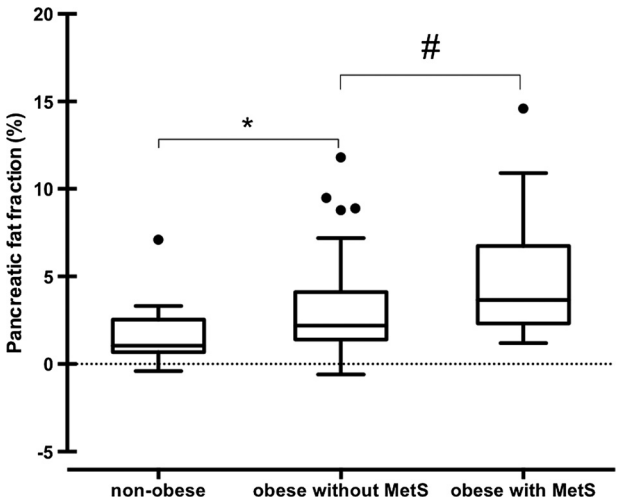

FIGURE 1. Pancreatic fat fraction and MetS. The graph demonstrates PFF in nonobese, obese non-Mets, and obese MetS subjects using a Tukey plot. *P = 0.0029, #P = 0.0156.

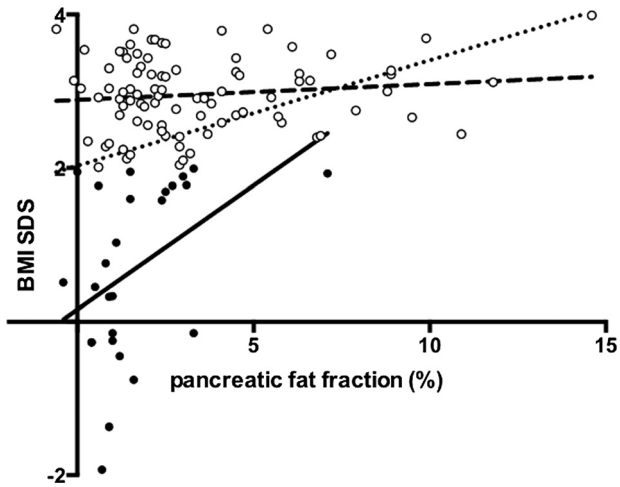

FIGURE 3. Scatter plot and regression lines of BMI-SDS and pancreas fat when considering the different groups. Nonobese: full circles and full line. Obese: open circles, dashed line. Whole study group: dotted line.

previous findings[5] and warrants further investigations. Generally, subjects with MetS have an increased risk of type 2 diabetes mellitus.[34] In adults, PFF has been shown to be highest in subjects with diabetes.[14] Recent pediatric studies have demonstrated that prediabetic subjects have higher PFF.[6,35] However, when adjusted regression analyses were performed by Pacifico et al,[6] only liver fat remained significantly correlated to prediabetes. In the present study, no significant relationship between PFF and IGT was found; however, we demonstrate a positive correlation between PFF and fasting plasma glucose as well as PFF and IFG, which need further longitudinal investigation in larger cohorts with regard to causality and pathophysiological impact.

We found that LFF was approximately 4 times higher and PFF at least 2 times higher in subjects with obesity (Table 1). Previous studies have reported a weak or nonexisting correlation between ectopic fat deposition in the pancreas and liver.[5,9] Here, we observe a correlation between these depots in subjects without obesity, suggesting that early deposition of ectopic fat is not organ specific. Indeed, PFF has also previously been associated to hepatic steatosis in adults.[36] We also discovered a positive correlation in the whole cohort, but interestingly not within the obesity subcohort (Fig. 2), implying that once obesity is overt, ectopic fat deposition is more organ selective, possibly because of genetic factors.[37] Our results are in agreement with data reported by Pacifico et al.[6] Furthermore, we report that PFF and VAT show a significant association, which has also been demonstrated previously.[7] Given the close proximity between these depots, this association was expected, but whether VAT is the main cause of PFF still remains to be elucidated.

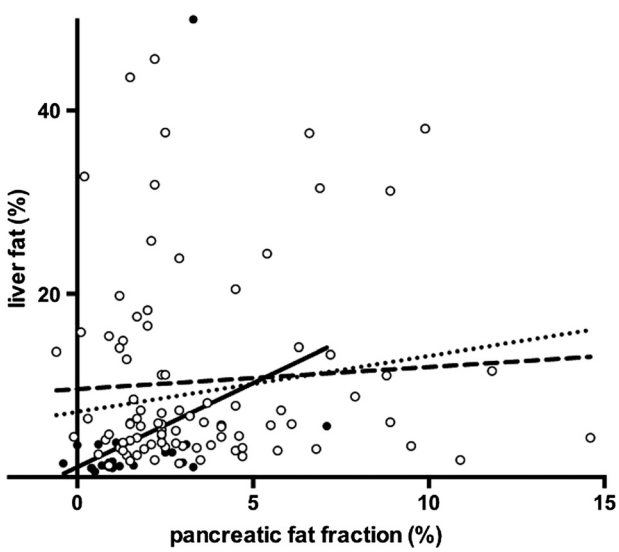

FIGURE 2. Scatter plot and regression lines of liver fat and pancreas fat when considering the different groups. Nonobese: full circles and full line. Obese: open circles, dashed line. Whole study group: dotted line.

Previously, a positive correlation between BMI and PFF was observed.[38] Interestingly, in the present study, PFF is higher in subjects with obesity compared with subjects without obesity, yet in the obesity subcohort, no association between PFF and BMI-SDS was established (Table 2) (Fig. 3) despite the relatively wide range of BMI-SDS in this subcohort. This indicates that once obesity is present in adolescence, accumulation of pancreas fat is driven by other factors than total body fat. One relatively small-sized pediatric study has previously reported a difference in PFF between subjects with and without obesity; however, the correlation between PFF and BMI-SDS in regression analysis has not been investigated.[5] Furthermore, the present study demonstrates that the associations of PFF to other parameters in simple regression models are highly dependent on BMI characteristics of the cohort studied. This could serve as explanation of previously reported conflicting results regarding the association between PFF and estimates of BCF and IR in heterogeneous cohorts.

Multiple techniques can be applied to quantify adipose tissue. With the use of MRI, PFF can accurately be determined and studied in relation to metabolic abnormalities.[3] Previously, PFF has been measured using computed tomography,[12] magnetic resonance spectroscopy,[9,11] and MRI.[4,5,10,39] Among these, MRI is advantageous because it allows analysis of lipid-specific signals from a large section of the pancreas without using ionizing radiation. The PFF varied between approximately 0% (absent) to 15% in this study. Previously reported amounts of PFF differ; in pediatric subjects, maximum values of 7% to 14.4% have been reported,[5,10] and adults show similar maximum values.[8,38–40] One

single study, which used magnetic resonance spectroscopy, reported maximum PFF of more than 50%.[9]

This study is one of the largest examining PFF with MRI in children, but results must be interpreted with some limitations in mind. Subjects were recruited at 2 European sites; however, all examinations were harmonized and carried out according to standard operations procedures. Furthermore, in both subcohorts the range in BMI-SDS was relatively wide (Fig. 3). Because PFF did not correlate with age in either subcohort, puberty was not taken into consideration. Other limitations are that no clamps were conducted, which is the criterion-standard method to assess insulin secretion and resistance and that ethnicity was not controlled for.

We conclude that adolescent subjects with obesity have elevated PFF that is not associated to BCF or IR. Rather, PFF is associated to MetS and VAT. This association study also identified an interesting association to fasting glucose level that warrants further evaluation and demonstrates that conclusions regarding PFF and its associations are highly dependent on BMI-SDS of the studied cohort.

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