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Behind BMI: The Potential Indicative Role of Abdominal Ectopic Fat on Glucose Metabolism

Xiaoyang Li Hao Ren Hui Xu Xinjun Han Jun Lu Zhenghan Yang

Beijing Friendship Hospital, Capital Medical University, Beijing, China

Keywords
Magnetic resonance imaging · Obesity · Ectopic fat · Fat distribution

Abstract
Introduction: The purpose of this study was to compare the difference in abdominal fat distribution between different metabolic groups and find the ectopic fat with the most risk significance. ***Methods:*** A total of 98 subjects were enrolled; there were 53 cases in the normal glucose metabolism group and 45 cases in the abnormal glucose metabolism group. Chemical shift-encoded magnetic resonance imaging was applied for quantification of pancreatic fat fraction (PFF) and hepatic fat fraction (HFF), subcutaneous adipose tissue (SAT), and visceral adipose tissue (VAT). The correlation and the difference of fat distribution between different metabolism groups were analyzed. The receiver operating characteristic (ROC) curve was used to analyze the suggestive effect of different body fat fraction. ***Results:*** Correlation analysis showed that body mass index (BMI) had the strongest correlation with fasting insulin (r = 0.473, p < 0.001), HOMA-IR (r = 0.363, p < 0.001), and C-reactive protein (r = 0.245, p < 0.05). Pancreatic fat has a good correlation with fasting blood glucose (r = 0.247, p < 0.05) and HbA1c (r = 0.363, p < 0.001). With the increase of BMI, PFF, VAT, and SAT showed a clear upward trend, but liver fat was distributed relatively more randomly. The pancreatic fat content in the abnormal glucose metabolism group is significantly higher than that in the normal group, and pancreatic fat is also a reliable indicator of abnormal glucose metabolism, especially in the normal and overweight groups (the area under the curve was 0.859 and 0.864, respectively). ***Conclusion:*** MR-based fat quantification techniques can provide additional information on fat distribution. There are differences in fat distribution among people with different metabolic status. People with more severe pancreatic fat deposition have a higher risk of glucose metabolism disorders.

Introduction

Today's social conditions, overnutrition, and lack of a healthy lifestyle lead to a rapid rise in the prevalence of obesity, which has become a major health challenge due to the increased risk of associated diseases, such as metabolic syndrome including type 2 diabetes mellitus (T2DM), hypertension, and even the risk of death [1]. The prevalence of type 2 diabetes in obese adults is 3–7 times higher than that in normal weight adults [2]. Study [3] has shown that patients with T2DM have more

Xiaoyang Li and Hao Ren contributed equally to this study and are listed as co-first authors.

karger@karger.com
www.karger.com/ofa

Correspondence to:
Zhenghan Yang, yangzhenghan@vip.163.com

visceral adipose tissue (VAT) and less subcutaneous adipose tissue (SAT) than nondiabetic healthy controls, and that VAT is important because it is associated with increased inflammatory factors and oxidative stress, it represents a higher risk of disease [4–6]. Studies have found that although body mass index (BMI) is normal, some people also show the clustering of metabolic and cardiovascular risk factors, such as insulin resistance and dyslipidemia, which may be related to the increase of adipose tissue other than subcutaneous [7]. Therefore, studying the details of fat distribution can improve our understanding of the mechanisms and development of metabolic disorders such as obesity and diabetes.

In the study of organ ectopic fat deposition, the liver has received more attention. The associated clinical liver dysfunction is called nonalcoholic fatty liver disease, is also considered to be often associated with T2DM, and the prevalence of nonalcoholic fatty liver disease in T2DM patients is as high as 75% [8]. Both excessive intra-abdominal fat and liver fat in T2DM patients are associated with ectopic fat deposition [9, 10]. In recent years, the pancreas has gradually become a research hotspot [11–15]. However, due to the lack of unified quantitative standards, some studies have reported inconsistent results when exploring the direct relationship between metabolic disorders and liver and pancreatic fat content [12, 13, 16–18]. The lack of uniformity of various imaging modalities may also be an important reason for this situation [19, 20].

Currently, magnetic resonance imaging (MRI) is the preferred choice for accurate quantification of adipose tissue [13, 21], and commonly used techniques such as proton density fat fraction (PDFF) technique are a novel method for water-fat separation with six echoes [16, 22]. Idilman reported that PDFF technique could accurately quantify liver fat deposition and observed a good correlation between liver magnetic resonance spectroscopy and liver biopsy [22]. Similarly, PDFF technique can also be used to measure pancreatic fat content and has good consistency with biopsy results [23]. However, previous studies have not paid enough attention to the difference between pancreatic fat distribution and liver; pancreatic fat distribution is heterogeneous, and the whole pancreas should be evaluated to obtain more stable results [21]. So as to ensure the repeatability and accuracy of the results to the greatest extent, differences in region of interest (ROI) selection will further reduce the comparability between different studies.

Therefore, the objectives of this study were to: (i) quantify SAT, VAT, hepatic fat fraction (HFF), and pancreatic fat fraction (PFF) using MRI and to investigate their associations with glucose and lipid metabolism; (ii) evaluate the differences in fat distribution among different glucose metabolism groups; (iii) evaluate the suggestive role of fat deposition at different sites in abnormal glucose metabolism.

Materials and Methods

Subjects

This study was approved by the Ethics Committee, and informed consent was obtained from all enrolled patients. All study methods were performed in accordance with approved guidelines. After exclusion criteria (see below), 98 subjects were enrolled and divided into two groups, they are patients at our institution from November 2021 to March 2023. There were 45 cases in the abnormal glucose metabolism group (10 males and 35 females, aged 52.8 ± 12.6 years, range 20–68 years; all were newly diagnosed and untreated) and 53 cases in the normal glucose metabolism group (25 males and 28 females, aged 44.6 ± 12.0 years, range 23–67 years). Abnormal glucose metabolism includes elevated fasting blood glucose (FBG), elevated HbA1c, impaired glucose tolerance, and diabetes. The classification and diagnosis of glucose metabolism status were based on the criteria of the 2020 edition of the Chinese Guidelines for the Prevention and Treatment of Type 2 Diabetes [24].

Study Criteria

All subjects had no history of alcohol or drug addiction, and the following conditions were excluded: (1) acute infections; (2) the presence of definite cardiovascular and cerebrovascular diseases; (3) use of any medications that alter insulin sensitivity; (4) any space-occupying disease or malignant tumor of the liver, pancreas, and kidney; (5) body weight changes significantly within a short period of time or history of bariatric surgery; (6) claustrophobia, the presence of any metallic material in the body (such as pacemakers, defibrillators, aneurysm clips, and certain prostheses contraindicated by MRI).

Clinical and Biochemical Data

The images of all subjects were acquired completely, and the image signal-to-noise ratio was sufficient. On the day of MRI examination, fasting biochemical tests were completed, including FBG, HbA1c, fasting insulin (FINS), C-reactive protein (CRP), and HOMA-IR was defined as (Gluc × Ins)/22.5. Routine lipid metabolism data were also collected, including total cholesterol, triglyceride, high-density lipoprotein, low-density lipoprotein. The demographic data (age, gender, BMI) were recorded. The BMI of Chinese standard (normal BMI: 18–23.9 kg/m^2; overweight: 24–27.9 kg/m^2; obesity: >28 kg/m^2).

MRI Examination

All subjects were scanned on a 3.0T field strength MRI (750W, GE Healthcare, Milwaukee, WI, USA) using a 32-channel receiving array coil. All subjects fasted for at least 6 h before scanning and performed breath-holding training. All scans were completed by a trained technician. All patients underwent MRI scan covering the diaphragm to the third lumbar spine in the supine position. Triplanar localization

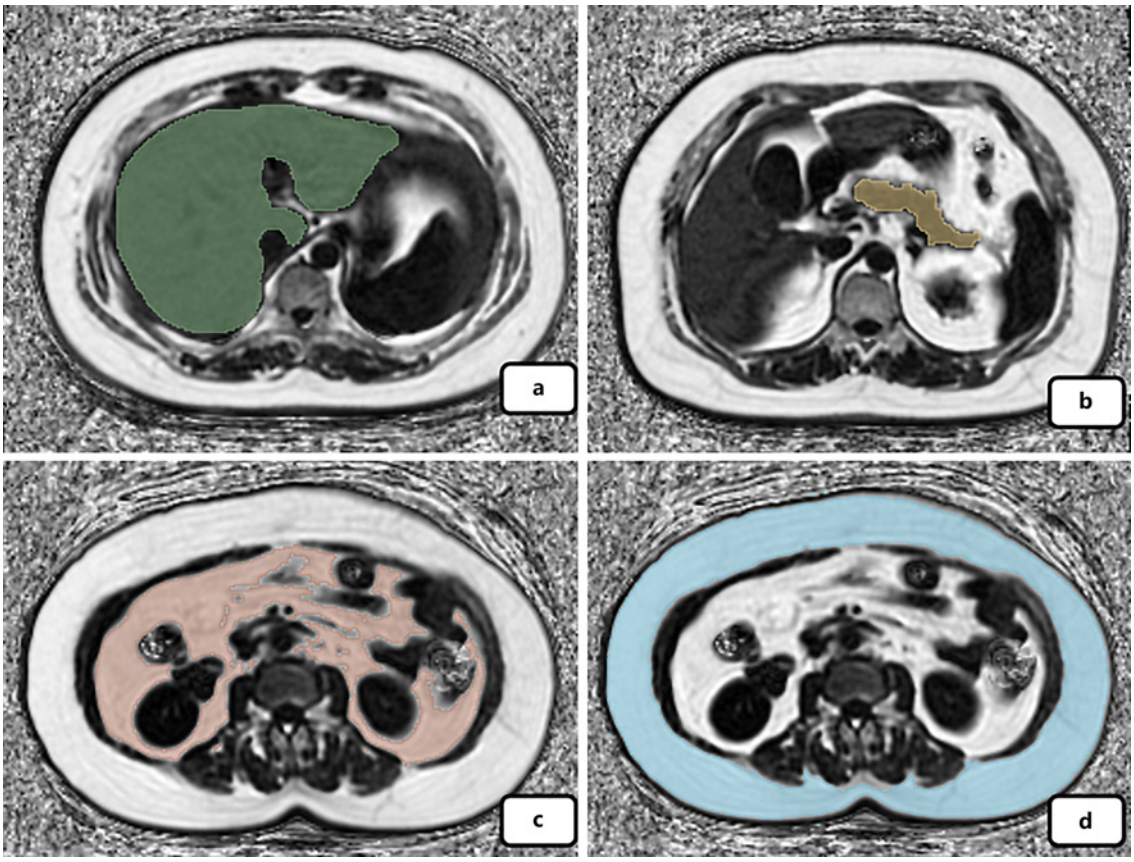

Fig. 1. a Example image: full coverage of the ROI at all levels of the liver (green area), assessing the overall liver fat content to avoid ROI sampling errors. **b** Similar to the liver, the ROI covered the entire pancreas as finely as possible. **c** The colored part indicates the measurement range of visceral fat, and "the visceral fat area/the body cross-sectional area of the layer ×100%" represents the visceral fat fraction, which can eliminate the influence caused by different body sizes. **d** The sky blue area indicates the measurement range of subcutaneous fat.

imaging was performed at the beginning of the examination, and the final PDFF sequence was obtained, with a slice thickness of 6 mm and containing aqueous phase, fat phase, in-phase, and out-phase images, as well as PDFF sequence.

Measurement of SAT, VAT, HFF, and PFF

Abdominal fat was quantified using the image analysis software 3D Slicer (version 4.11.1; http://www.slicer.org). Image processing was performed by an experienced radiologist. The liver, pancreas, visceral and subcutaneous fat were segmented by 3D Slicer software, and the hepatic fat fraction (HFF), PFF, VAT, and SAT were quantified, which were expressed as percentage (%). After each scan, the system automatically performs post-processing using a software package provided by the vendor and generates a report containing the fat fraction values. The details are as follows (Fig. 1a–d):

1. HFF: the liver was delineated at each level where the liver appeared from top to bottom, with the ROI covering the entire liver. The radiomics software package in the 3D Slicer program can quantify fat in the ROI and generate reports to obtain fat fraction.
2. PFF: similar to the liver, ROI was delineated for the whole pancreas, attention should be paid to avoiding the accompanying vessels, especially the splenic vein, and the tissue boundary can be identified with the help of in-phase sequences.
3. VAT: choose the level of the lumbar spine 2/3 intervertebral disc (close to the maximum waist circumference in the supine state), the area of visceral fat was automatically delineated by 3D Slicer, and the body cross-sectional area of this layer was obtained. The degree of visceral fat accumulation was represented by the visceral fat area/the body cross-sectional area ×100%.
4. SAT: the ROI was subcutaneous fat, and the rest was equivalent to visceral fat.

Statistical Analysis

SPSS (V25.0, IBM, Chicago, IL) software, GraphPad Prism 9.2.0 (GraphPad Software, San Diego, CA, USA) software, and G*power (V3.1.9.7) software was used for statistical analysis. Pearson correlation coefficient was used to evaluate the correlation of BMI and fat fraction in different parts with laboratory indicators. *t* test was used to evaluate the difference in fat distribution between the

Table 1. Baseline characteristics of the study population grouped by glucose metabolism status

Variable	Normal group (N = 53)	Abnormal group (N = 45)	p value
Gender (male:female)	25:28	10:35	
Age, years	44.6±12.0	52.8±12.6	<0.05
BMI, kg/m^2	27.58±4.31	28.04±4.92	0.626
FBG, mmol/L	5.18±0.47	7.08±1.92	<0.001
HbA1c, %	5.39±0.40	7.10±1.34	<0.001
FINS, uIU/mL	17.16±12.32	22.33±13.41	<0.05
HOMA-IR	3.98±2.98	6.87±3.96	<0.001
CRP, ng/mL	3.53±2.57	3.64±1.39	0.813
TC, mmol/L	4.94±1.02	5.46±1.12	<0.05
TG, mmol/L	1.84±0.89	1.93±0.89	0.593
HDL, mmol/L	1.12±0.23	1.11±0.22	0.775
LDL, mmol/L	2.95±0.73	3.31±0.78	<0.05
HFF, %	14.28±7.82	15.28±6.44	0.495
PFF, %	12.35±5.81	17.32±5.78	<0.001
SAT, %	20.74±5.86	22.20±5.48	0.208
VAT, %	18.20±5.83	19.87±5.86	0.164

Continuous variables were normally distributed and expressed as mean ± standard deviation, and categorical variables were expressed as numbers; independent sample t tests were used for continuous variables. Significance was defined as $p < 0.05$. BMI, body mass index; FBG, fasting blood glucose; HbA1c, hemoglobin A1c; FINS, fasting insulin; HOMA-IR, homeostasis model assessment of insulin resistance; CRP, C-reactive protein; TC, total cholesterol; TG, triglycerides; HDL, high-density cholesterol; LDL, low-density lipoprotein cholesterol; HFF, hepatic fat fraction; PFF, pancreatic fat fraction; SAT, subcutaneous adipose tissue; VAT, visceral adipose tissue.

abnormal glucose metabolism group and the normal glucose metabolism control group. For subgroup small sample comparison, power analysis was further used. A linear fit was used to describe the trend of change. The area under the curve (AUC) and its 95% confidence interval were obtained by analyzing the receiver operating characteristic (ROC) of the variable, and the cutoff value was calculated. Odds ratios with 95% confidence intervals were extrapolated. Significance was defined as $p < 0.05$.

Results

Correlation Analysis

Table 1 presents the descriptive results for normal and abnormal group, respectively, according to the glucose metabolism. Table 2 shows the correlation of BMI and fat fraction in different parts with various laboratory indicators. BMI had the strongest correlation with FINS ($r = 0.473$, $p < 0.001$), HOMA-IR ($r = 0.363$, $p < 0.001$), and C-reactive protein ($r = 0.245$, $p = 0.015$). Compared with other measured fat fractions, pancreatic fat had a certain correlation with biochemical indicators of glucose metabolism, and the correlation between pancreatic fat and FBG ($r = 0.247$, $p = 0.014$) and HbA1c ($r = 0.363$, $p < 0.001$) was stronger, which suggested that with the aggravation of pancreatic fat deposition, the blood glucose control was worse. Liver fat was correlated with C-reactive protein ($r = 0.233$, $p = 0.021$). Visceral fat and subcutaneous fat were correlated with FINS and HOMA-IR, but the correlations are weak. However, there was no clear correlation between conventional lipid metabolism indicators.

The Trend of Body Fat with the Increase of BMI

Figure 2 shows the linear fitting plot based on all subjects. At lower BMI, the abdominal fat distribution was SAT > HFF > VAT > PFF. With the increase of BMI, PFF, VAT, and SAT showed a clear upward trend, especially SAT, suggesting that the subcutaneous may be an important site of excess fat storage. Pearson correlation analysis showed that BMI was positively correlated with PFF ($r = 0.272$, $p = 0.007$), VAT ($r = 0.519$, $p < 0.001$), and SAT ($r = 0.613$, $p < 0.001$). With the increase of BMI, ectopic fat deposition was more obvious in the pancreas than in the liver. It may be difficult to observe the changes of BMI and fat distribution in an individual, and the population trends revealed in this study may be of reference value.

Table 2. Pearson correlation analysis of BMI and body fat fraction with different metabolic indicators in all subjects

	FBG	HbA1c	FINS	HOMA-IR	CRP	TC	TG	HDL	LDL
BMI									
Correlation coefficient	−0.106	0.039	**0.473[a]**	**0.363[a]**	**0.245***	−0.026	−0.139	−0.161	0.041
p value	0.297	0.700	0.000	0.000	0.015	0.801	0.173	0.114	0.688
HFF (%)									
Correlation coefficient	0.064	0.006	−0.025	−0.010	0.233*	0.127	0.178	−0.114	0.153
p value	0.534	0.952	0.803	0.919	0.021	0.213	0.079	0.262	0.134
PFF (%)									
Correlation coefficient	**0.247***	**0.363[a]**	0.297[a]	0.349[a]	−0.009	0.007	−0.031	−0.171	0.032
p value	0.014	0.000	0.003	0.000	0.931	0.944	0.759	0.091	0.753
SAT (%)									
Correlation coefficient	−0.065	0.084	0.408[a]	0.328[a]	0.196	0.028	−0.119	0.017	0.060
p value	0.526	0.410	0.000	0.001	0.053	0.781	0.242	0.865	0.558
VAT (%)									
Correlation coefficient	0.021	0.030	0.365[a]	0.329[a]	0.124	0.036	−0.049	0.047	0.060
p value	0.835	0.771	0.000	0.001	0.225	0.725	0.632	0.645	0.556

BMI, Body mass index; HFF, Hepatic fat fraction; PFF, Pancreatic fat fraction; SAT, subcutaneous adipose tissue; VAT, Visceral adipose tissue; FBG, Fasting blood glucose; HbA1c, Hemoglobin A1c; FINS, Fasting insulin; HOMA-IR, Homeostasis model assessment of insulin resistance; CRP, C-reactive protein; TC, Total cholesterol; TG, Triglycerides; HDL, High density cholesterol; LDL, Low-density lipoprotein cholesterol. [a]Represents significant correlation at the 0.01 level. The most relevant parts are indicated in bold. * represents significant correlation at the 0.05 level.

Differences in Fat Distribution

All the subjects were divided into three groups according to BMI, and the differences in fat distribution under different glucose metabolism conditions are shown in Table 3 and Figure 3. *t* test and power analysis results showed that in the normal weight group, there were differences in PFF ($p = 0.012$, power = 0.766) and SAT ($p = 0.045$, power = 0.536) between the normal glucose metabolism group and the abnormal glucose metabolism group, and the pancreatic fat and subcutaneous fat of the abnormal metabolism group were higher than those of the normal glucose metabolism group. In the overweight group, there was a significant difference in pancreatic fat content ($p < 0.001$, power = 0.999), and the pancreatic fat content in the abnormal glucose metabolism group was significantly higher than that in the normal metabolism group with the same BMI. In the obese group, the fat content of all parts was higher, and there was no significant difference between the different metabolic groups. Surprisingly, liver fat content was not a good predictor in either group, whereas pancreatic fat was more strongly associated with disorders of glucose metabolism.

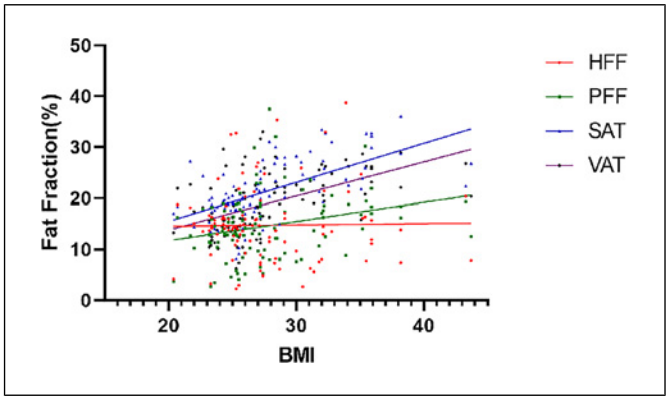

Fig. 2. Linear trend plots of fat deposition at different sites with increasing BMI. The response of visceral fat, subcutaneous fat, and pancreatic fat to BMI was more obvious.

Potential Relationship between Pancreatic Fat and Glucose Metabolism

The linear fitting of glucose metabolism indexes based on pancreatic fat is shown in Figure 4. According to the correlation analysis results, HbA1c and FINS are positively correlated with pancreatic fat. But beyond the correlation

Table 3. Differences in fat distribution

	Normal glucose metabolism	Abnormal glucose metabolism	*p* value
Normal weight (*n* = 16)	*n* = 8	*n* = 8	
HFF, %	15.425±2.201	12.701±6.870	0.304
PFF, %	8.940±4.983	14.990±3.210	**0.012**[a]
SAT, %	16.144±2.550	19.830±3.985	**0.045**[a]
VAT, %	14.085±4.003	15.931±4.795	0.411
Overweight (*n* = 49)	*n* = 27	*n* = 22	
HFF, %	14.651±7.981	15.184±4.852	0.785
PFF, %	10.550±4.221	18.585±6.256	**0.000**[b]
SAT, %	18.397±4.875	19.690±3.141	0.288
VAT, %	15.394±4.657	18.278±6.073	0.138
Obesity (*n* = 33)	*n* = 18	*n* = 15	
HFF, %	14.417±8.296	15.3387±9.612	0.769
PFF, %	16.575±6.008	16.703±5.920	0.952
SAT, %	26.309±3.798	27.161±5.664	0.610
VAT, %	22.404±3.490	24.293±2.708	0.098

Continuous variables were normally distributed and expressed as mean ± standard deviation, and independent sample *t* tests were used for continuous variables. HFF, hepatic fat fraction; PFF, pancreatic fat fraction; SAT, subcutaneous adipose tissue; VAT, visceral adipose tissue. [a]Represents significant correlation at the 0.05 level. [b]Represents significant correlation at the 0.01 level.

analysis, the linear fit of pancreatic fat to FINS provided additional information, as FINS levels showed a trend of first increasing and then decreasing with increasing pancreatic fat. Peak insulin secretion may occur as a normal response to obesity but decreases after excess fat accumulation.

ROC Curve Analysis

1. ROC curve was used to analyze BMI and fat fraction (liver, pancreas, visceral and subcutaneous fat) to indicate the risk of abnormal glucose metabolism (Fig. 5a–d). In all subjects, PFF showed the best effect, and the AUC for indicating abnormal glucose metabolism was 0.750, and the difference was statistically significant ($p < 0.01$). The optimal threshold to predict abnormal glucose metabolism was 14.11%, with a sensitivity of 73.33% and a specificity of 69.81%.
2. In the normal weight group, the AUC of PFF for indicating abnormal glucose metabolism was 0.859, and the difference was statistically significant ($p < 0.05$). The optimal threshold to predict abnormal glucose metabolism was 11.38%, with a sensitivity of 87.50% and a specificity of 75.00%.
3. In the overweight group, the AUC of PFF for indicating abnormal glucose metabolism was 0.864, and the difference was statistically significant ($p < 0.01$). The optimal threshold to predict abnormal glucose metabolism was 14.11%, with a sensitivity of 77.27% and a specificity of 81.48%.
4. In the obesity group, the predictive power of BMI was higher than others, but the AUC for predicting abnormal glucose metabolism was only 0.659, and the difference was not statistically significant ($p > 0.05$).

Discussion

Currently, ectopic adipose tissue deposition is considered to be one of the major factors in glucose metabolism disorders [25, 26]. A study with whole-body analysis confirmed that ectopic fat deposition in the abdomen (central obesity) was more closely related to metabolic syndrome [27]. Among the abdominal organs, the liver and pancreas are important organs for maintaining metabolic balance in the human body. Considering the focal accumulation of adipose tissue in the organs and its possible impact on endocrine function, as well as excessive ectopic fat destroying various pathways in gluconeogenesis, the assessment of fat content of the pancreas and liver has attracted much attention [13]. On the other hand, the effects

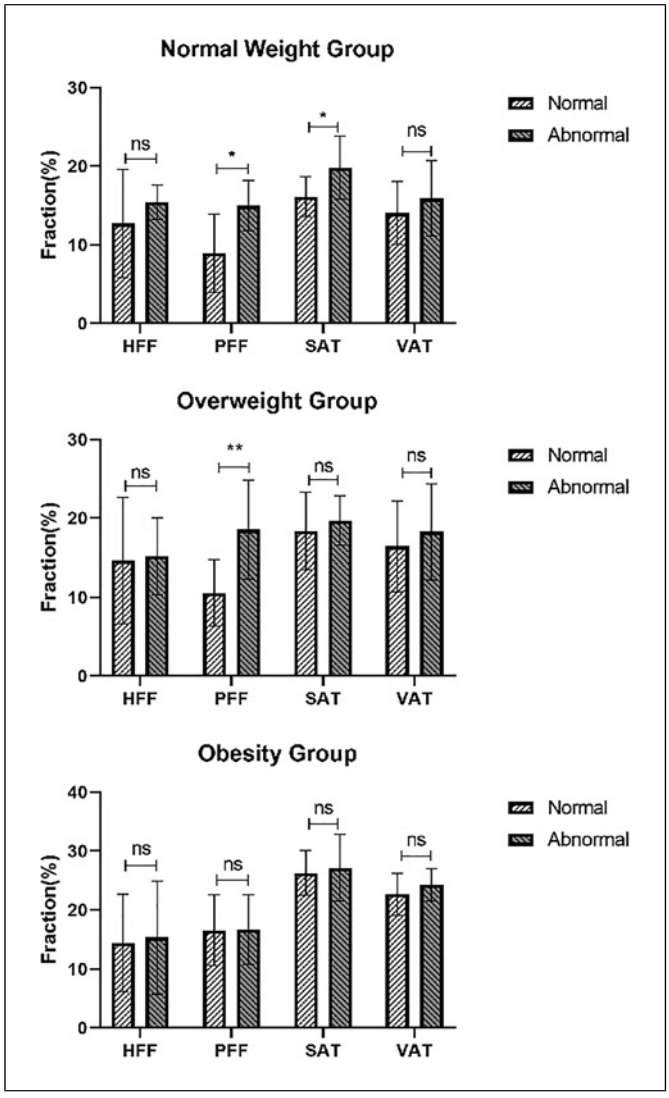

Fig. 3. Visualized bar graphs of fat fraction in different groups. *Represents significant differences at the 0.05 level. **Represents significant difference at the 0.01 level, and ns represents no significant difference. There were significant differences in SAT and PFF in the normal weight group and in PFF in the overweight group.

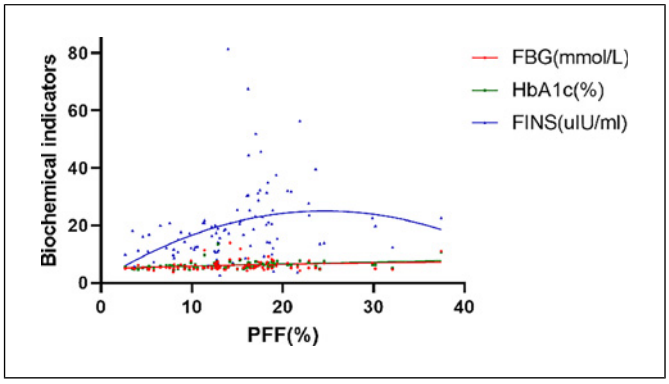

Fig. 4. Linear fitting of pancreatic fat and glucose metabolism indicators showed that FINS eventually showed a downward trend as pancreatic fat increased.

brought by subcutaneous fat are different from those brought by visceral fat [28]. Visceral fat has limited expansibility, whereas subcutaneous tissue can accommodate more fat [29]. Therefore, it is of significance to sort out the changing trend of subcutaneous fat and visceral fat and the influence of different fat distribution patterns on metabolic function.

The results of this study showed that pancreatic fat has an important suggestive effect on glucose metabolism disorders, and PFF is closely related to glycosylated hemoglobin, which means that pancreatic fat deposition may be related to poor blood glucose control. Honka Henri [30, 31] also verified similar results. However, he also pointed out that some studies showed inconsistent results [31], and the reason was probably due to measurement error caused by the heterogeneity of fat distribution. This study avoided this interference factor as much as possible through the overall evaluation, and the results were of reference value. At the same time, when the pancreatic fat infiltration is within a certain limit, its insulin secretion function can still maintain a high level, even showing hyperinsulinemia, which is also suggested by the results of this study [32], and the insulin secretion level also decreases when the pancreatic fat content is excessive. This suggests that pancreatic fat deposition and the resulting lipotoxicity may play an important role in the late stage of islet cell dysfunction [33].

Although the mechanism of type 2 diabetes is complex and many key knowledge gaps regarding hyperinsulinemia and insulin resistance remain to be explored [34], this study shows that BMI may still be an important factor in the assessment of hyperinsulinemia and insulin resistance, and high BMI often indicates more severe insulin resistance in clinical practice. Moreover, with the increase of BMI, VAT, SAT, and PFF showed a positive linear correlation, while the response of liver fat to weight change was relatively irregular. The reason may be that as the liver is the main organ of energy metabolism in the human body, the dysfunction of adipocytes, lipodystrophy, and lack of adipose tissue will lead to changes in liver fat content [35–37]. In addition, the results of a weight loss study

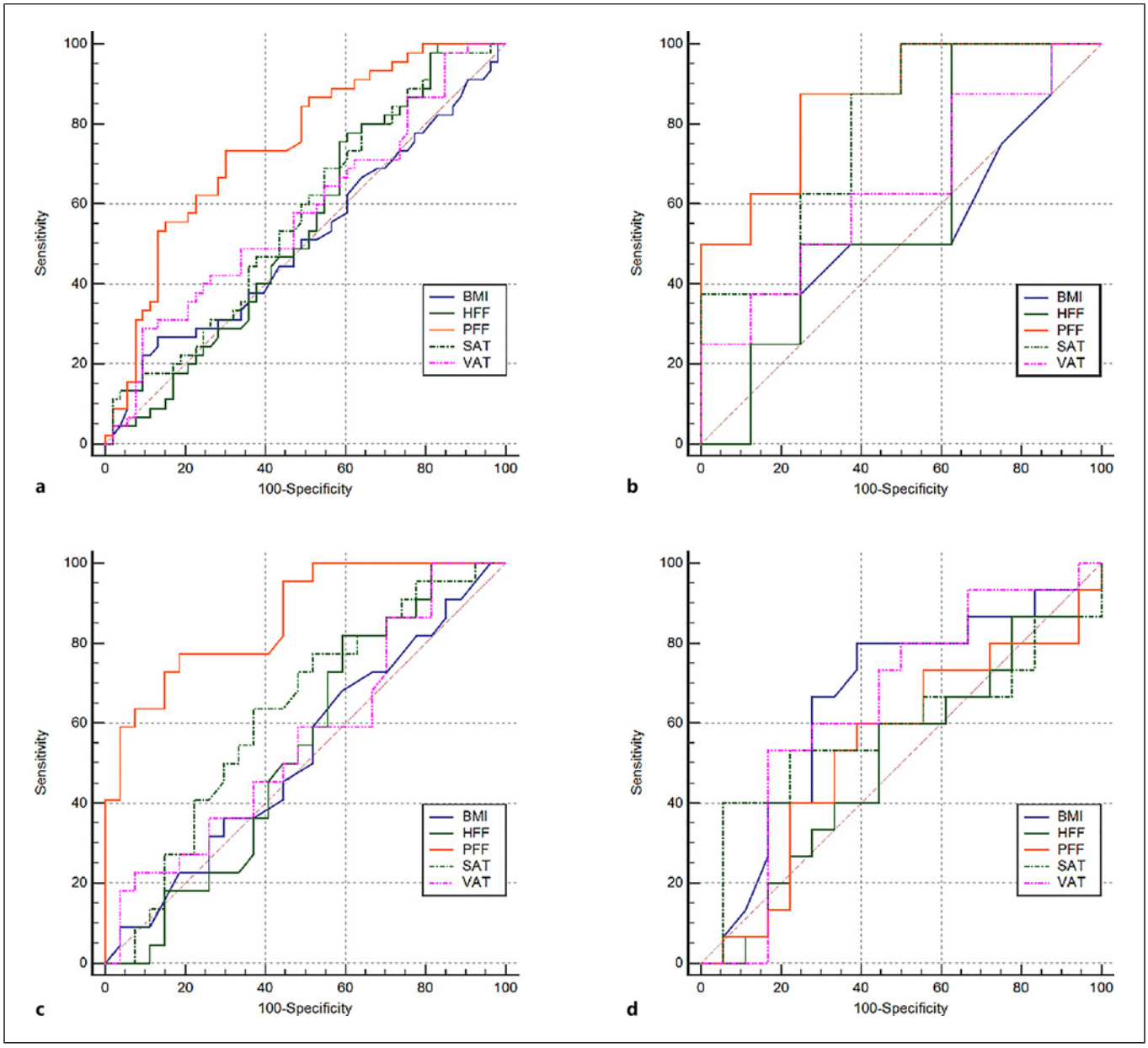

Fig. 5. ROC curves of BMI, HFF, PFF, VAT, and SAT for predicting abnormal glucose metabolism in different groups. **a** In all subjects, the AUC for BMI was 0.512 (95% CI, 0.409–0.615), HFF was 0.542 (95% CI, 0.438–0.643), PFF was 0.750 (95% CI, 0.650–0.830), VAT was 0.578 (95% CI, 0.474–0.678), and SAT was 0.571 (95% CI, 0.467–0.671). **b** In normal weight group, the AUC for BMI was 0.516 (95% CI, 0.259–0.766), HFF was 0.594 (95% CI, 0.326–0.826), PFF was 0.859 (95% CI, 0.598–0.979), VAT was 0.641 (95% CI, 0.369–0.859), and SAT was 0.781 (95% CI, 0.509–0.944). **c** In overweight group, the AUC for BMI was 0.525 (95% CI, 0.378–0.670), HFF was 0.540 (95% CI, 0.392–0.684), PFF was 0.864 (95% CI, 0.736–0.945), VAT was 0.561 (95% CI, 0.412–0.703) and SAT was 0.625 (95% CI, 0.475–0.759). **d** In obesity group, the AUC for BMI was 0.659 (95% CI, 0.474–0.814), HFF was 0.504 (95% CI, 0.325–0.682), PFF was 0.541 (95% CI, 0.359–0.715), VAT was 0.648 (95% CI, 0.463–0.806), and SAT was 0.585 (95% CI, 0.401–0.753). CI, confidence interval.

showed significant reductions in both liver and pancreatic fat in those who lost weight in a short period of time [38]. This study points to reduced pancreatic fat as a secondary consequence of reduced outward transport of hepatic triglycerides; therefore, the change of liver fat may be different from other organs.

At the same time, there were significant differences in pancreatic fat among different metabolic groups, especially in normal weight group and overweight group. When excessive pancreatic fat deposition was observed in these groups, it often suggested the risk of abnormal glucose metabolism. For the risk prediction of abnormal glucose metabolism, the indicative function of the pancreas was better than others, and the AUC was 0.750 in the whole group, 0.859 in the normal weight group and 0.864 in the overweight group. Compared with obese people, normal weight group and overweight group are often not paid attention to in metabolic screening, but the increased prevalence of metabolic diseases in Asian population is more closely related to body fat distribution than BMI [39]. Imaging examination can better pay attention to important information of fat distribution, which BMI cannot provide. As a more accustomed concern in daily work, HFF has a lower significance than PFF in suggesting abnormal glucose metabolism.

The quantification of visceral fat is also one of the current research hotspots. Some studies have proposed that the predictive effect of VAT collected at the level of the third lumbar spine is higher than that of any other level [40], but there are still other suggestions for the selection of VAT level [41, 42], and its measurement is easily affected by gastrointestinal activity and other factors. Shen also proposed that there are differences between intraperitoneal adipose tissue and extraperitoneal adipose tissue [43]. The fact that the extraperitoneal adipose tissue is mainly a mechanical buffer for organs and the intraperitoneal adipose tissue component has significant metabolic activity suggests that the evaluation of the fat distribution pattern needs to be further refined.

This report has several limitations. First, our study had a relatively small sample size because of strict enrollment criteria, which required medical history investigation for each enrolled patient and exclusion of multiple medical conditions. The small sample size may be accompanied by outcome bias, and further studies with larger sample sizes are needed to obtain more accurate results. Second, this study was a cross-sectional study, and no longitudinal observation was performed. During the follow-up, if any patients received weight loss treatment, the changes in fat distribution should be further followed up to determine its effect in evaluating the prognosis. Finally, the costs and time required to perform MRI limit its widespread use in the general population.

Conclusion

In general, the fat measurement sites selected in this study can be easily obtained, the measurement technology is mature, and it is a reliable method for assessing fat distribution. At the same time, the study cohort has excluded a variety of interference factors, and the results show that pancreatic fat has great potential in the evaluation of glucose metabolism. Noninvasive MRI assessment of fat distribution helps identify individualized predictors of underlying metabolic diseases.

Statement of Ethics

This study was approved by the Ethics Committee of Beijing Friendship Hospital (ID: 2019-P2-229-01), Capital Medical University, and written informed consent was obtained from all enrolled patients. All study methods were performed in accordance with approved guidelines.

Conflict of Interest Statement

The authors have no conflicts of interest to declare.

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Author Contributions

Conception and design: X. Li; administrative support: H. Xu and Z. Yang; provision of study materials or patients and collection and assembly of data: X. Li and H. Ren; data analysis and interpretation: X. Li, X. Han, and J. Lu; and manuscript writing and final approval of the manuscript: all authors.

Data Availability Statement

All data generated or analyzed during this study are included in this article. Further inquiries can be directed to the corresponding author.

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