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ORIGINAL ARTICLE

Association of built environment characteristics with adiposity and glycaemic measures

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Summary

Objective

This study examined the cross-sectional and longitudinal relationships of built environment characteristics with adiposity and glycaemic measures.

Method

Longitudinal study sample consisted of 4,010 Framingham Heart Study Offspring (baseline: 1998–2001; follow-up: 2005–2008) and Generation Three (baseline: 2002–2005; follow-up: 2008–2011) participants (54.8% women, baseline mean age 48.6 years). Built environment characteristics (intersection density, greenspace, recreation land and food stores) at baseline were collected. Adiposity and glycaemic measures (body mass index [BMI], waist circumference, abdominal subcutaneous and visceral adipose tissue, and fasting plasma glucose) at baseline and changes during 6.4-year follow-up were measured.

Results

In cross-sectional models, higher intersection density and food store density (total food stores, fast food restaurants and supermarkets) were linearly associated with higher BMI (all $p < 0.05$). Higher greenspace was associated with lower BMI, waist circumference, fasting plasma glucose, prevalent obesity and prevalent diabetes (all $p < 0.05$). Longitudinally, higher intersection density and food store density, and lower greenspace were associated with smaller increases in abdominal visceral adipose tissue (all $p < 0.05$). Higher densities of intersections, fast food restaurants and supermarkets were associated with smaller increases in fasting plasma glucose (all $p < 0.05$).

Conclusions

Collectively, built environment characteristics are associated with adiposity and glycaemic traits, suggesting the potential mechanisms by which built environment influences cardiometabolic health.

Keywords: Diabetes, obesity, subcutaneous adipose tissue, visceral adipose tissue.

Introduction

Obesity and diabetes have increased exponentially over the last several decades at a rate that would suggest contributing factors beyond individual-level characteristics (1,2). Some research has identified neighbourhood environmental factors as potential influences on the distribution of obesity-related cardiovascular risk across populations (3) and disparities in obesity and diabetes rates in different geographical regions (4,5). Researchers have examined several components of built environment, such as intersection density, greenspace, recreation land and local food environment, to explore relationships, patterns and trends in obesity (6,7) and diabetes (6,8).

One major limitation of prior research regarding the association of the built environment with health-related conditions has been the lack of measures of adiposity beyond body mass index (BMI) (9–13) and waist circumference (10,11,14). Obesity is a heterogeneous condition, in which individuals with similar BMI may have distinct metabolic and cardiovascular disease risk (15,16). In prior studies, variations in body fat distribution assessed by abdominal subcutaneous adipose tissue (SAT) and visceral adipose tissue (VAT) provided a potential explanation for increased risk for prevalent and incident cardiometabolic risk factors, incident cardiovascular disease and cancer even after accounting for multiple confounders (15,17,18), supporting the pathogenic properties of region-specific fat deposition. Accordingly, exploring the relationship between built environment features and abdominal adipose tissue may help decipher the multifactorial aetiology of obesity.

Therefore, the primary purpose of this study was to examine the associations between characteristics of built environment with adiposity and diabetes using the Framingham Heart Study, a community-based prospective study. The aims of the study were to explore the cross-sectional and longitudinal association between intersection density, greenspace, recreation land and food store elements in the built environment, with adiposity measures and diabetes. The hypothesis was that characteristics of built environment, including greater intersection density, greater greenspace and recreation land, and higher food store density would be associated with healthier levels of adiposity (BMI, waist circumference, SAT and VAT volume) and glycaemic measures (fasting plasma glucose) at baseline and during follow-up.

Methods

Study sample

Participants for this study were drawn from the Offspring and Generation Three cohorts of the Framingham Heart Study who resided in Massachusetts at the time of the clinic visits. Offspring participants were the children (or spouses of children) of the Original cohort, enrolled starting in 1971. The Generation Three cohort participants were the grandchildren of the Original cohort, with enrollment starting in 2002. For the purposes of this study, the baseline exposure data for the late 1990s/early 2001s were available; thus, baseline began with the seventh examination for the Offspring cohort and the first examination of the Generation Three cohort.

Among the participants who attended the baseline examination (Offspring seventh examination [1998–2001] and Generation Three first examination [2002–2005]), information on built environment was available for 5,435 participants. Among these, a total of 4,010 attended the follow-up examinations (Offspring eighth examination [2005–2008] and the Generation Three second examination [2008–2011]).

For the longitudinal component of the study, different study populations had the following outcome data available: (i) change in fasting plasma glucose and incident diabetes (n = 4,010); (ii) changes in BMI and waist circumference (n = 3,953); and (iii) changes in abdominal SAT and VAT volumes (n = 1,274).

The study protocol was approved by the institutional review boards of the Boston University Medical Center and Massachusetts General Hospital. All participants provided written informed consent.

Built environment characteristics

Utilizing the 2000 US Census TIGER/Line files (19), we obtained self-reported residential addresses during the clinical visit at the baseline examination for this study. The census tract and census block group of each residential address were identified. For the analysis, intersection density, greenspace and recreation land within the boundary of the census block group were identified (13). Because of the low concentration of food stores in the neighbourhood, food stores within the boundary of the census tract were assessed (20). Intersection density was defined as number of intersections in census block group per square kilometre. Greenspace was defined as percentage of greenspace in census block group. Recreation land was defined as percentage of recreation land in census block group. Food store elements were defined as number of food stores in census tract per square kilometre. More detailed information on built environment characteristics is included in the Supporting Information.

Assessment of adiposity and glycaemic measures

Adiposity and glycaemic measures were available from Framingham Heart Study at the baseline and follow-up examinations for the study. Adiposity measures included objectively measured or calculated BMI (weight in kilograms/height in square metre), obesity (BMI $\geq$30 kg m^{-2}) and waist circumference (distance around the abdomen at the horizontal level of the umbilicus to the nearest 0.25 in.). The abdominal SAT and VAT volumes were quantified from the abdominal scans acquired via an eight-slice multi-detector computed tomography (MDCT) (LightSpeed Ultra, General Electric, Milwaukee, WI, USA) (21). A trained reader outlined the abdominal muscular wall from the abdominal scan to differentiate and quantify the abdominal SAT and VAT via a three-dimensional Workstation tool by utilizing a semi-automatic method (Aquarius 3D Workstation, TeraRecon Inc., San Mateo, CA, USA). The high reproducibility of these two fat measures was previously reported elsewhere with inter-reader and intra-reader reliability of ≥0.99 for both abdominal SAT and VAT volumes (21).

Blood samples collected after a minimum of 8 h of overnight fasting were used to evaluate fasting plasma glucose. Diabetes mellitus was defined as (i) fasting plasma glucose ≥126 mg dL^{-1}; (ii) nonfasting plasma glucose ≥200 mg dL^{-1} when fasting plasma glucose status was not available; or (iii) use of glucose-lowering medication.

Changes in adiposity and glycaemic measures were computed by subtracting the baseline values from the follow-up values. Incident diabetes was computed based on the number of new cases of diabetes at follow-up divided by the number of persons at risk for the risk factor.

Covariates

All covariates were assessed at the baseline examination cycle. Current smoking was defined as smoking at least one cigarette per day in the year preceding the examination. As an indirect measure of socioeconomic status, educational attainment was collected based on the highest attained educational level according to the following categories: <high school, high school graduate, associate's degree, ≥college degree or other. Cohort status was dichotomized as Offspring or Generation Three cohort.

Statistical analysis

A majority of distributions of the built environment characteristics were skewed, and several extreme outliers were detected. As a result, quartiles for these measures were calculated. For the regression analyses, the reference value was assigned as quartile 1, which was the lowest value for built environment characteristics.

Linear regression was used to characterize the associations between characteristics of built environment and continuous outcome variables (BMI, waist circumference, SAT, VAT and fasting plasma glucose) and logistic regression for associations between characteristics of built environment and dichotomous outcome variables (obesity and diabetes), adjusting for age, gender, smoking status, education and cohort status. Except for BMI and obesity models, all models were adjusted for BMI. For the longitudinal study design, relevant baseline values were additionally adjusted in the models. For example, for the models of glucose change and incident diabetes model, baseline fasting plasma glucose was included in the model, and for the SAT change model, baseline SAT volume was included in the model. The tests for identifying gender interactions were constructed based on the model adjusted for age, gender, smoking status, education and cohort status.

The level of significance was considered as two-tailed, $p < 0.05$. This significance level was not further adjusted for multiple testing as the purpose of this investigation was principally hypothesis generating (i.e. to explore potential associations between built environment characteristics with adiposity and glycaemic measures). All the statistical analyses were performed using SAS software, version 9.3 (SAS Institute, Cary, NC, USA).

Results

Descriptive characteristics

Table 1 displays the baseline characteristics of the 4,010 longitudinal study participants (54.8% women). The mean age (standard deviation [SD]) of the participants was 48.6 years (13.0 years) at baseline and 54.9 years (14.0 years) at follow-up. The average increase (SD) in adiposity and glycaemic measures during 6.4 years (SD 0.7 years) of follow-up period was 0.8 kg m^{-2} (2.4 kg m^{-2}) for BMI, 3.4 cm (6.8 cm) for waist circumference, 566 cm^3 (691 cm^3) for SAT, 686 cm^3 (743 cm^3) for VAT and 3.6 mg dL^{-1} (11.3 mg dL^{-1}) for fasting plasma glucose. Among the 4,010 participants without diabetes at baseline, 174 (4.3%) developed diabetes during follow-up. The characteristics of the 5,435 cross-sectional study participants (53.6% women) are shown in Table S1.

Cross-sectional associations

Higher quartiles of greenspace were associated with lower BMI, waist circumference and fasting plasma glucose (all p for linear trend < 0.05) (Table S2), which were in the expected direction. Higher quartiles of intersection density and food store density (total food stores, fast food restaurants and supermarkets) were linearly associated with higher BMI (all p for linear trend < 0.05); these associations were not in the expected direction.

The highest quartile of greenspace was associated with decreased odds of prevalent obesity and diabetes compared with the lowest quartile (p for linear trend < 0.05) (Table S3). The highest quartile of recreation land, as compared with the lowest quartile, was associated with decreased odds of obesity (odds ratio [OR] 0.80, 95% confidence interval [CI] 0.68, 0.95). As compared with the lowest quartile, the highest quartile of intersection density, total food stores and fast food restaurants was associated with increased odds of

Table 1 Baseline characteristics of the longitudinal study participants

Characteristics	Overall study participants (n = 4,010)
Sociodemographics	
Age (years)	48.6 (13.0)
Women (%)	54.8 (2197)
Current smoking (%)	14.6 (584)
Education (%)	
<High school	2.0 (80)
High school graduate	22.4 (898)
Associate's degree	32.8 (1314)
≥College degree	42.5 (1705)
Other	0.3 (13)
Built environment	
Intersection density*,† (count km^{-2})	9.9 (5.5, 20.5)
Greenspace*,‡ (%)	54.5 (36.7, 69.2)
Recreation land*,‡ (%)	4.2 (1.2, 10.3)
Food store elements*,§ (count km^{-2})	
Total food stores	0.50 (0.18, 1.30)
Full service restaurants	0.18 (0.05, 0.54)
Fast food restaurants	0.12 (0.04, 0.36)
Supermarkets	0.05 (0.01, 0.14)
Convenience stores	0.03 (0.00, 0.08)
Adiposity and glycaemic measures	
Body mass index (kg m^{-2})	27.4 (5.1)
Waist circumference (cm)	95.5 (14.2)
Subcutaneous adipose tissue (cm^3)	2894 (1357)
Visceral adipose tissue (cm^3)	1787 (986)
Fasting plasma glucose (mg dL^{-1})	95.0 (9.5)
Obesity (%)	24.7 (991)

Characteristics of built environment were assessed based on 2000 US Census data. Unless otherwise indicated, continuous variables are shown as means (standard deviations) and dichotomous variables are shown as percentages (counts).
*Data are shown as medians (25th, 75th percentiles) because of their skewed distribution.
†Defined as number of intersections in census block group per square kilometre.
‡Defined as percentage of greenspace or recreation land in census block group.
§Defined as number of food store elements in census tract per square kilometre.

prevalent obesity (OR 1.24, 95% CI 1.04, 1.47, for intersection density; OR 1.27, 95% CI 1.07, 1.51, for total food stores; and OR 1.36, 95% CI 1.14, 1.61, for fast food restaurants).

Longitudinal associations

All of the characteristics of built environment, except recreation land, were consistently associated with changes in abdominal VAT during the follow-up (all p for linear trend < 0.05) (Table 2). Higher food store density (overall and separately for each specific food establishment type) was associated with smaller changes in abdominal VAT during follow-up (all p for linear trend < 0.05). From the lowest to highest quartiles of supermarket density, the mean changes (standard error) in VAT volume were 763 cm^3 (35 cm^3), 692 cm^3 (35 cm^3), 706 cm^3 (37 cm^3) and 577 cm^3 (36 cm^3), respectively (p for linear trend = 0.002). Trends were similar for all other food store establishments. In addition, higher intersection density, fast food restaurant density and supermarket density were associated with smaller fasting plasma glucose change (p for linear trend < 0.05). None of the other adiposity measures were longitudinally associated with built environment characteristics.

Multivariable-adjusted logistic regression models for characteristics of built environment and incident diabetes are shown in Table 3. Consistently, built environment characteristics were not linearly associated with incident diabetes (all p for linear trend > 0.05).

Gender interaction

For the cross-sectional study design, a majority of the gender interactions were statistically non-significant, except intersection density with BMI (p = 0.03) and waist circumference (p = 0.01); recreation land with VAT (p = 0.01); total food stores with BMI (p = 0.003) and waist circumference (p = 0.001); full service restaurants with BMI (p = 0.02) and waist circumference (p = 0.01); fast food restaurants with BMI (p = 0.02) and waist circumference (p = 0.01); and supermarkets with BMI (p = 0.04) and waist circumference (p = 0.04). These associations tended to be stronger in women than in men.

For the longitudinal study design, none of the gender interactions were significant, with the exception of intersection density with BMI change (p = 0.02), and convenience stores with waist circumference change (p = 0.03). In the gender-stratified models, the associations between intersection density with BMI change and convenience stores with waist circumference change were not significant in both women and men ($p > 0.05$).

Discussion

In this examination of Framingham Heart Study participants, characteristics of built environment were cross-sectionally and longitudinally associated with adiposity and glycaemic measures. The directionality of the associations was not consistent for the cross-sectional and longitudinal findings. Cross-sectionally, higher intersection density and food store density, and lower greenspace were associated with higher adiposity and glycaemic measures. Longitudinally, higher

Table 2 Longitudinal associations between build environment characteristics with changes in adiposity and glycaemic measures

Exposures*	Outcomes	Least square means (standard errors)				*p* for linear trend
		Quartile 1	Quartile 2	Quartile 3	Quartile 4	
Intersection density	Δ in body mass index	0.7 (0.1)	1.0 (0.1)	0.9 (0.1)	0.7 (0.1)	0.77
	Δ in waist circumference	3.0 (0.2)	3.9 (0.2)	3.5 (0.2)	3.4 (0.2)	0.53
	Δ in subcutaneous adipose tissue	508 (37)	607 (38)	641 (40)	514 (40)	0.69
	Δ in visceral adipose tissue	706 (34)	739 (35)	690 (37)	599 (37)	0.02
	Δ in fasting plasma glucose	3.6 (0.3)	4.4 (0.3)	3.3 (0.4)	3.0 (0.4)	0.03
Greenspace	Δ in body mass index	0.7 (0.1)	0.8 (0.1)	0.9 (0.1)	0.8 (0.1)	0.31
	Δ in waist circumference	3.4 (0.2)	3.5 (0.2)	3.6 (0.2)	3.3 (0.2)	0.85
	Δ in subcutaneous adipose tissue	531 (40)	629 (37)	560 (40)	536 (37)	0.62
	Δ in visceral adipose tissue	619 (38)	685 (34)	686 (38)	743 (35)	0.03
	Δ in fasting plasma glucose	3.3 (0.4)	3.6 (0.4)	3.8 (0.3)	3.5 (0.4)	0.48
Recreation land	Δ in body mass index	0.9 (0.1)	0.9 (0.1)	0.8 (0.1)	0.7 (0.1)	0.07
	Δ in waist circumference	3.6 (0.2)	3.6 (0.2)	3.4 (0.2)	3.1 (0.2)	0.06
	Δ in subcutaneous adipose tissue	552 (40)	615 (38)	548 (38)	550 (37)	0.56
	Δ in visceral adipose tissue	664 (38)	696 (36)	696 (36)	686 (35)	0.70
	Δ in fasting plasma glucose	3.4 (0.3)	3.2 (0.4)	4.0 (0.4)	3.6 (0.3)	0.34
Total food stores	Δ in body mass index	0.9 (0.1)	0.8 (0.1)	0.9 (0.1)	0.7 (0.1)	0.28
	Δ in waist circumference	3.5 (0.2)	3.4 (0.2)	3.5 (0.2)	3.3 (0.2)	0.65
	Δ in subcutaneous adipose tissue	527 (37)	640 (39)	559 (39)	541 (40)	0.66
	Δ in visceral adipose tissue	691 (34)	783 (36)	665 (36)	597 (37)	0.01
	Δ in fasting plasma glucose	3.8 (0.3)	4.1 (0.3)	3.3 (0.4)	3.1 (0.4)	0.06
Full service restaurants	Δ in body mass index	0.8 (0.1)	0.8 (0.1)	0.9 (0.1)	0.7 (0.1)	0.52
	Δ in waist circumference	3.4 (0.2)	3.5 (0.2)	3.6 (0.2)	3.2 (0.2)	0.72
	Δ in subcutaneous adipose tissue	558 (36)	609 (42)	558 (36)	546 (41)	0.53
	Δ in visceral adipose tissue	711 (34)	729 (39)	694 (34)	604 (38)	0.03
	Δ in fasting plasma glucose	3.8 (0.3)	3.5 (0.4)	3.5 (0.3)	3.4 (0.4)	0.57
Fast food restaurants	Δ in body mass index	0.9 (0.1)	0.8 (0.1)	0.8 (0.1)	0.8 (0.1)	0.28
	Δ in waist circumference	3.6 (0.2)	3.5 (0.2)	3.3 (0.2)	3.5 (0.2)	0.60
	Δ in subcutaneous adipose tissue	523 (37)	626 (38)	544 (38)	572 (41)	0.90
	Δ in visceral adipose tissue	688 (35)	780 (35)	673 (36)	589 (38)	0.01
	Δ in fasting plasma glucose	3.8 (0.3)	4.1 (0.3)	3.3 (0.4)	3.0 (0.4)	0.02
Supermarkets	Δ in body mass index	0.9 (0.1)	0.9 (0.1)	0.7 (0.1)	0.7 (0.1)	0.005
	Δ in waist circumference	3.8 (0.2)	3.5 (0.2)	3.3 (0.2)	3.2 (0.2)	0.046
	Δ in subcutaneous adipose tissue	597 (38)	563 (37)	576 (39)	527 (39)	0.30
	Δ in visceral adipose tissue	763 (35)	692 (35)	706 (37)	577 (36)	0.002
	Δ in fasting plasma glucose	3.8 (0.3)	4.1 (0.3)	3.4 (0.4)	2.9 (0.4)	0.02
Convenience stores	Δ in body mass index	0.8 (0.1)	0.8 (0.1)	0.9 (0.1)	0.7 (0.1)	0.72
	Δ in waist circumference	3.4 (0.2)	3.4 (0.3)	3.7 (0.2)	3.3 (0.2)	0.99
	Δ in subcutaneous adipose tissue	574 (31)	573 (56)	570 (39)	546 (39)	0.62
	Δ in visceral adipose tissue	704 (29)	797 (52)	685 (36)	606 (36)	0.01
	Δ in fasting plasma glucose	3.5 (0.3)	3.6 (0.5)	3.9 (0.4)	3.3 (0.4)	0.76

Data are shown as multivariable-adjusted least squares means (standard errors). For example, from the lowest to highest quartiles of supermarket density, the mean changes in visceral adipose tissue volume were 763, 692, 706 and 577 cm^3, respectively. Multivariable-adjusted model was adjusted for baseline age, gender, smoking status at baseline, education at baseline, cohort status and baseline body mass index. Body mass index model was not adjusted for baseline body mass index. Model-specific adjustment included baseline fasting plasma glucose for fasting plasma glucose model; baseline waist circumference for waist circumference model; baseline subcutaneous adipose tissue volume for subcutaneous adipose tissue model; and baseline visceral adipose tissue volume for visceral adipose tissue model. Quartile 4 corresponds to greater intersection density, larger greenspace and recreation land, and higher food store density, as compared with quartile 1.

*Intersection density was defined as number of intersections in census block group per square kilometre. Greenspace was defined as percentage of greenspace in census block group. Recreation land was defined as percentage of recreation land in census block group. Food store elements were defined as number of food stores in census tract per square kilometre. Characteristics of built environment were assessed based on 2000 US Census data.

intersection density and food store density, and lower greenspace were associated with smaller changes in abdominal VAT during the follow-up. Higher intersection density and density of fast food restaurants and

Table 3 Longitudinal associations between built environment characteristics and incident diabetes

Exposures*	Quartile 1 (reference)	Quartile 2		Quartile 3		Quartile 4		*p* for linear trend
		OR	95% CI	OR	95% CI	OR	95% CI	
Intersection density	1	1.40	0.85, 2.30	1.11	0.68, 1.83	1.13	0.68, 1.88	0.88
Greenspace	1	0.98	0.61, 1.58	1.02	0.64, 1.64	0.70	0.41, 1.19	0.25
Recreation land	1	0.84	0.50, 1.39	1.09	0.67, 1.76	1.06	0.66, 1.70	0.58
Total food stores	1	0.93	0.57, 1.53	0.96	0.59, 1.58	0.97	0.59, 1.60	0.96
Full service restaurants	1	1.14	0.69, 1.90	0.94	0.58, 1.54	1.15	0.70, 1.89	0.77
Fast food restaurants	1	0.81	0.50, 1.32	0.85	0.52, 1.39	0.78	0.48, 1.28	0.40
Supermarkets	1	1.53	0.94, 2.50	1.49	0.91, 2.46	0.99	0.59, 1.67	0.92
Convenience stores	1	0.71	0.39, 1.31	1.11	0.72, 1.73	0.99	0.64, 1.53	0.82

Data are shown as odds ratios and 95% confidence intervals. For example, the highest quartile of intersection density is associated with 1.13-fold (95% confidence interval 0.68–1.88) increased odds of incident diabetes. Multivariable-adjusted model was adjusted for baseline age, gender, smoking status at baseline, education at baseline, cohort status, baseline fasting plasma glucose and baseline body mass index. Quartile 4 corresponds to greater intersection density, larger greenspace and recreation land, and higher food store density, as compared with quartile 1.

CI, confidence interval; OR, odds ratio.

*Intersection density was defined as number of intersections in census block group per square kilometre. Greenspace was defined as percentage of greenspace in census block group. Recreation land was defined as percentage of recreation land in census block group. Food store elements were defined as number of food stores in census tract per square kilometre. Characteristics of built environment were assessed based on 2000 US Census data.

supermarkets were longitudinally associated with smaller changes in fasting plasma glucose. Most notably in this study, characteristics of built environment were consistently associated with changes in abdominal VAT, but not with SAT, during 6.4 years of follow-up period. Taken together, the association between built environment characteristics with adiposity and glycaemic traits observed in this study demonstrates potential evidence that the built environment could influence cardiometabolic health but not always in the expected direction.

The vast majority of research exploring the associations between built environment with obesity and diabetes has been conducted using cross-sectional studies (14,22–24). Recently, there has been a growing body of literature exploring the longitudinal associations between built environment characteristics with obesity (9–12,25) and diabetes (8,26). Existing obesity studies primarily used the traditional anthropometric measurements, such as BMI (9,11–13) or waist circumference (10,11). These longitudinal studies highlighted the associations between characteristics of built environment, such as intersection density (10), fast food restaurants (9,10) and grocery stores (9) with changes in BMI and/or waist circumference. Nevertheless, conflicting findings were also reported with some of the characteristics of built environment (9,12). With the traditional anthropometric fat measurements, the only longitudinal association identified in this study was between high supermarket density with smaller changes in BMI and waist circumference.

In this study, a diverging relationship between cross-sectional and longitudinal findings was observed. Higher intersection density and food store density and less greenspace were associated with higher adiposity in the cross-sectional study but lower adiposity change in the longitudinal study (less increase in VAT over time). The differences in the direction of the associations between the cross-sectional and longitudinal findings may be due to the limitation in cross-sectional study design. More specifically, a cross-sectional study design only provides a snapshot of the association, limiting the ability to explore the influence of the long-term cumulative exposure of built environment characteristics on important health outcomes over time. As compared with longitudinal study settings, associations identified in the cross-sectional study may be more prone to reflect the residential self-selection bias, in which individuals with higher socioeconomic status tend to live in healthier and safer neighbourhoods (27,28). Furthermore, it is difficult to rule out the potential influence of neighbourhood-level socioeconomic status (29,30), psychosocial stress related to environment (31) and neighbourhood crime and safety (32) from the data that were collected at a single time point. Collectively, these contrasting results may suggest that in the context of built environment characteristics, the longitudinal study setting is more robust to explore the associations with health-related outcomes, such as obesity and diabetes.

To our knowledge, the present study is the first to explore the relationship between built environment characteristics with MDCT-assessed SAT and VAT volume, cross-sectionally and longitudinally. An intriguing association between built environment characteristics and changes in fat was observed, specifically in VAT change, but not with SAT change. These associations remained significant upon adjustment for BMI, suggesting that the features of built environment are associated with this pathogenically active fat depot above and beyond the contribution of systemic effect of adiposity. Abdominal VAT is an active endocrine fat depot that is closely associated with cardiovascular disease risk factors (15) and events (17). As compared with SAT, which is classified as non-ectopic fat depot, VAT is considered more problematic because of the unique pathogenic property of secreting active substances, such as pro-inflammatory adipokines (33), and haemostatic and fibrinolytic markers (34) that are closely related to manifestation of cardiometabolic disease. In addition, the non-significant cross-sectional association but significant longitudinal associations with VAT suggests that built environment characteristics may have a long-term cumulative effect on this unique pathogenic fat depot.

Consistent with our *a priori* hypothesis, higher intersection density was associated with smaller changes in adiposity and glycaemic measures during the follow-up, perhaps suggesting that physical activity mediates the relationship between intersection density of the neighbourhood and levels of adiposity and glycaemic measures (35). In contrast, more greenspace, an environmental factor that may associate with physical activity opportunity, stress reduction, social interaction and cohesion (36), had a larger increase in VAT volume during the follow-up. One explanation may be that greater greenspace reflects less urbanized areas with fewer facilities available at walking distance (37). Accordingly, individuals living in rural areas are more likely to have higher vehicle use rather than walking or cycling (35).

Furthermore, inconsistent cross-sectional and longitudinal results for food store density were found. Regardless of the classification of the food stores, higher food store density was associated with a smaller increase in the changes in VAT and/or fasting plasma glucose, i.e. less increase in adiposity over time. It is plausible that the higher food store density reflects more walkable neighbourhoods, thus demonstrating that these food stores are a proxy for intersection density. A lower density of food establishments in the neighbourhood may be an indicator of geographically disadvantaged food desert communities with limited access to healthy and affordable food or could simply be a proxy for poverty. The US Department of Agriculture's Economic Research Service noted that food desert tracts were associated with measures of low socioeconomic status, including lower rates of educational attainment and employment, as well as lower incomes (38). Accordingly, participants in neighbourhoods with greater accessibility and availability to the food sources could be demonstrating a link between higher income (not measured in this study) and less adiposity over time.

Previous studies showed non-significant associations between features of built environment with incident diabetes (8,26). Of note, a recent study from the Multi-Ethnic Study of Atherosclerosis with 5,124 participants explored the longitudinal association between actual food and physical activity resources in the neighbourhood and self-reported perceptions of these resources with incident diabetes during an 8.9-year follow-up period (8). Associations were significant for perceptions of the built environment but not with the measured geospatial data. Specifically, supermarkets and produce markets (hazard ratio [HR] 1.01, 95% CI 0.96, 1.07) and commercial recreation establishments (HR 0.98, HR 0.94, 1.03) were not associated with incident diabetes after adjusting for confounders and neighbourhood socioeconomic status (8), which were similar to the results found in this current study. Similar findings were noted between intersection density (residential density, street connectivity and land use mix) and incident diabetes in a large study with 512,061 Swedish adults (26). In this study, measures of built environment (intersection density, fast food restaurants and supermarkets) were associated with changes in fasting plasma glucose during follow-up, but not with incident diabetes. This discrepancy regarding the findings of dichotomous and continuous glycaemic measures may be due to the relatively small cases of incident diabetes and the use of quartile-based analysis, which may have substantially reduced the power to detect the associations. In addition, given that the mean age of the participants in this study was middle-aged adults, the 6.4-year follow-up period may not be sufficient to detect longitudinal associations with incident diabetes.

The strength of the present study is the use of a large and well-characterized community-based sample with reliable measures of MDCT-assessed abdominal fat at baseline and follow-up. The repeated measures of obesity and diabetes allowed us to examine the longitudinal associations between the features of built environment with adiposity and glycaemic measures during 6.4 years of follow-up. The study also had several limitations. Generalizability of the study findings to other ethnic groups may be limited as the current study sample was composed entirely of white participants, and this study only included participants living in Massachusetts. Causal inferences cannot be made based on the findings of the current study because of the nature of observational study design. Education was used as a proxy of individual-level socioeconomic status. The boundaries of census tracts and census block groups were used to assess the built environment characteristics. However, the administrative boundaries may differ from the actual neighbourhood boundaries and be vulnerable to a modifiable area unit problem (39). Because of the lack of individual-level census tract and census block group information, the statistical models could not be adjusted for random effects related to census tract and census block group. Inconsistent cross-sectional and longitudinal results were observed in this study. The lack of concordance between these two experimental designs may be partially due to the shortcomings of the experimental design or lack of accurate assessment of the variables, in particular the characteristics of built environment owing to the complexity of the data. This study examined the longitudinal association between baseline built environment characteristics and changes in adiposity and glycaemic measures. In order to speculate the reverse causality (i.e. healthier people move to healthier neighbourhoods) based on the observational data, statistical models that include baseline adiposity and glycaemic measures as exposures and changes in built environment characteristics during an extended follow-up period as outcome variables are required. Because our study lacked data on changes in built environment characteristics and also the follow-up period was only 6.4 years, potential investigation of reverse causality was not possible. Further studies that incorporate changes in the built environment during an extended follow-up period are warranted to assess whether neighbourhood change is associated with incidence of obesity and diabetes, as well as to assess the reverse causality.

Conclusions

Characteristics of built environment, including intersection density, greenspace and food store elements, are cross-sectionally and longitudinally associated with measures of adiposity and diabetes at baseline and changes during follow-up. These findings add a novel framework to the spectrum of the relationships between built environment characteristics and obesity by demonstrating a unique association with an ectopic fat depot assessed by MDCT. The findings from this study provide an additional foundation to the potential mechanism by which built environment impacts cardiometabolic health.

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Conflict of Interest Statement

Caroline S. Fox became an employee of Merck Research Labs on 14 December 2015. There is nothing to disclose for any author other than Caroline S. Fox.

NHLBI Disclaimer

The views expressed in this manuscript are those of the authors and do not necessarily represent the views of the National Heart, Lung, and Blood Institute; National Institutes of Health; or the US Department of Health and Human Services.

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Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article.

Table S1. Baseline characteristics of the cross-sectional study participants
Table S2. Cross-sectional associations between build environment characteristics with adiposity and glycemic measures
Table S3. Cross-sectional associations between built environment characteristics with prevalent obesity and diabetes