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Mendelian Randomization

Associations of obesity and circulating insulin and glucose with breast cancer risk: a Mendelian randomization analysis

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Abstract

Background: In addition to the established association between general obesity and breast cancer risk, central obesity and circulating fasting insulin and glucose have been linked to the development of this common malignancy. Findings from previous studies, however, have been inconsistent, and the nature of the associations is unclear.

Methods: We conducted Mendelian randomization analyses to evaluate the association of breast cancer risk, using genetic instruments, with fasting insulin, fasting glucose, 2-h glucose, body mass index (BMI) and BMI-adjusted waist-hip-ratio (WHR_{adj BMI}). We first

confirmed the association of these instruments with type 2 diabetes risk in a large diabetes genome-wide association study consortium. We then investigated their associations with breast cancer risk using individual-level data obtained from 98 842 cases and 83 464 controls of European descent in the Breast Cancer Association Consortium.

Results: All sets of instruments were associated with risk of type 2 diabetes. Associations with breast cancer risk were found for genetically predicted fasting insulin [odds ratio (OR) = 1.71 per standard deviation (SD) increase, 95% confidence interval (CI) = 1.26-2.31, $p = 5.09 \times 10^{-4}$], 2-h glucose (OR = 1.80 per SD increase, 95% CI = 1.30-2.49, $p = 4.02 \times 10^{-4}$), BMI (OR = 0.70 per 5-unit increase, 95% CI = 0.65-0.76, $p = 5.05 \times 10^{-19}$) and $\text{WHR}_{\text{adj BMI}}$ (OR = 0.85, 95% CI = 0.79-0.91, $p = 9.22 \times 10^{-6}$). Stratified analyses showed that genetically predicted fasting insulin was more closely related to risk of estrogen-receptor [ER]-positive cancer, whereas the associations with instruments of 2-h glucose, BMI and $\text{WHR}_{\text{adj BMI}}$ were consistent regardless of age, menopausal status, estrogen receptor status and family history of breast cancer.

Conclusions: We confirmed the previously reported inverse association of genetically predicted BMI with breast cancer risk, and showed a positive association of genetically predicted fasting insulin and 2-h glucose and an inverse association of $\text{WHR}_{\text{adj BMI}}$ with breast cancer risk. Our study suggests that genetically determined obesity and glucose/insulin-related traits have an important role in the aetiology of breast cancer.

Key words: Breast cancer, insulin, glucose, obesity, genetics, Mendelian randomization analysis

Key Messages

- Mendelian randomization studies eliminate potential influence of reverse causation on study results and are less susceptible to bias and confounding than conventional observational studies. We used this approach to evaluate the association of obesity and glucose/insulin-related traits with breast cancer risk, using the data of a large consortium.
- We found genetically predicted fasting insulin and 2-h glucose levels were positively associated with breast cancer risk, whereas genetically predicted body mass index and waist-hip-ratio with adjustment of BMI were inversely associated with the risk.
- Our study has uncovered complex inter-relations of genetics, obesity, and breast cancer risk, and has provided novel findings regarding roles of circulating glucose and insulin in the risk of this common cancer.

Introduction

General and central obesity have been linked to breast cancer risk in previous studies.^{1,2} Body mass index (BMI) and waist-hip-ratio (WHR) are commonly used to measure general and central obesity, respectively. Obesity, particularly central obesity, is a major risk factor for insulin resistance and type 2 diabetes, which are often characterized by elevated fasting insulin and glucose as well as impaired glucose tolerance (usually measured by blood glucose level 2 h after oral glucose challenge).³ Previous studies have linked fasting insulin and glucose levels to increased risks of multiple cancers.⁴⁻⁶ Proposed mechanisms for these associations include cancer-promoting effects mediated by insulin and insulin-like growth factor (IGF) signalling pathways.⁷ However, the relationship between these

biomarkers and breast cancer remains controversial and findings from epidemiological studies are inconsistent.^{8,9} Concerns regarding the validity of these observational study findings include potential selection biases, reverse causation, confounding effects, small sample size and differences in assays used to measure the biomarkers of interest.

Mendelian randomization analysis has been used to evaluate potential causal relationships between exposures and disease.^{10,11} Genetic variants are used as instrumental variables in the analysis. Random assortment of alleles at the time of gamete formation results in a random assignment of exposures that are related to an allele (or a set of alleles). Thus, Mendelian randomization analyses may reduce potential biases that would afflict conventional

observational studies. In the current study, we performed Mendelian randomization analyses to assess associations of obesity (i.e. BMI and WHR) and glucose/insulin-related traits (i.e. fasting glucose, 2-h glucose and fasting insulin) with breast cancer risk, using data from the Breast Cancer Association Consortium (BCAC).

Methods

Study population

Included in this analysis are 182 306 participants of European ancestry, whose samples were genotyped using custom Illumina iSelect genotyping arrays: OncoArray (56 762 cases and 43 207 controls) or iCOGS array (42 080 cases and 40 257 controls). Institutional review boards of all involved institutions approved the studies. Selected characteristics of the two datasets are presented in [Supplementary Table 1](#), available as [Supplementary data](#) at *IJE* online. Details of the genotyping protocols in the BCAC are described elsewhere (iCOGS: <http://ccge.medschl.cam.ac.uk/research/consortia/icogs/>; OncoArray: <https://epi.grants.cancer.gov/oncoarray/>).^{12,13} Genotyping data were imputed using the program IMPUTE2¹⁴ with the 1000 Genomes Project Phase III integrated variant set as the reference panel. Single nucleotide polymorphisms (SNPs) with low imputation quality (imputation $r^2 < 0.5$) were excluded. Top principal components (PCs) were included as covariates in regression analysis to address potential population substructure (iCOGS: top eight PCs; OncoArray: top 15 PCs).

Selection of SNPs associated with glucose/insulin-related traits

In December 2016, we searched the National Human Genome Research Institute-European Bioinformatics Institute Catalog of Published Genome-Wide Association Studies and the literature for SNPs associated with the following traits: levels of 2-h glucose (2hrGlu), fasting glucose (FG), fasting insulin (FI), BMI and waist-hip-ratio with adjustment of BMI (WHR_{adj BMI}).^{15–19} SNPs associated with any of these traits at the genome-wide significance level ($P < 5 \times 10^{-8}$) in populations of European ancestry were included. For each GWAS-identified locus, a representative SNP with the lowest P -value in the original GWAS publication was selected (linkage disequilibrium $r^2 < 0.1$, based on 1000 Genome Phase III CEU data).

Construction of instrumental variables

Weighted polygenic scores for each trait (i.e. wPRS-2hrGlu, wPRS-FG, wPRS-FI, wPRS-BMI and wPRS-WHR_{adj BMI}) were constructed following the formula:

$wPRS\text{-trait}_i = \sum_i \beta_{i,GX} * SNP_i$, where $\beta_{i,GX}$ is the beta coefficient of the i^{th} SNP for the trait of interest from the published GWAS ([Supplementary Table 2](#), available as [Supplementary data](#) at *IJE* online). SNP_i is the imputed dosage of the effect allele in BCAC data (range: 0 to 2). To reduce potential pleiotropic effects, we excluded BMI- and WHR_{adj BMI}-associated SNPs from instruments of 2hrGlu, fasting glucose and insulin ($r^2 < 0.8$), and vice versa. The pleiotropic SNPs associated with more than one trait are presented in [Supplementary Table 2](#), available as [Supplementary data](#) at *IJE* online. The F-statistic was taken to indicate whether an instrumental variable was well-powered for Mendelian randomization analysis, with 10 being a commonly used threshold.²⁰ Variance explained (%) and F statistics for a specific trait were calculated following the formulae: $\sum_i 2 * \beta_{i,GX}^2 * f_{\text{effect allele}} * \frac{(1 - f_{\text{effect allele}})}{\text{var}(X)}$ * 100 and $R^2 * (n-1-k)/(1-R^2)/k$, respectively, where: R^2 is percentage of variance explained by used SNPs; f is the frequency of the effect allele reported by GWAS for the trait; $\text{var}(X)$ is the variance of trait, see below; n is the sample size of BCAC data; and k is the number of SNPs used in the instrument.²¹

For 2-h glucose, fasting glucose and insulin, $\beta_{i,GX}$ were further transformed to represent 1 standard deviation (SD) increase with the unit in the original GWAS (2-h glucose: 1 SD = 2 mmol/L, variance = 4; fasting glucose: 1 SD = 0.65 mmol/L, variance = 0.42; fasting insulin: 1 SD = 0.60 ln[pmol/L], variance = 0.36)^{17,22} by the formula: $\beta_{i,SD} = \beta_{i,GX} [2 * f(SNP_i)(1 - f(SNP_i))]^{0.5} / SD$. wPRS-BMI and wPRS-WHR_{adj BMI} represented the adjusted 1-SD increase of transformed BMI and WHR_{adj BMI}, as the original GWAS performed the inverse normal transformation for both phenotypes.^{18,19,23} We further scaled wPRS-BMI to be equivalent to five units of BMI by performing a linear regression among controls in our dataset: observed BMI \sim wPRS-BMI + error. Then we calculated the transformed BMI as $BMI_{wPRS} = \beta_0 + \beta_1 * (\text{wPRS-BMI})$, where β_0 and β_1 are slope and coefficient from the linear regression model mentioned above, respectively.

Statistical analysis

Given an established association between impaired glucose/insulin traits and type 2 diabetes, an association between constructed instruments and risk of type 2 diabetes is to be expected. We used summary statistics from the Diabetes Genetics Replication And Meta-analysis (DIAGRAM) Consortium and conducted a Mendelian randomization analysis of our traits using the inverse-variance-weighted two-sample method.^{10,24} The Mendelian randomization estimate and standard error were calculated as $\sum_i \beta_{i,GX} * \beta_{i,GY} * \sigma_{i,GY}^{-2} / (\sum_i \beta_{i,GX}^2 * \sigma_{i,GY}^{-2})$ and $1 / (\sum_i \beta_{i,GX}^2 * \sigma_{i,GY}^{-2})^{0.5}$, respectively. GY represents the association between a SNP

and type 2 diabetes risk; thus $\beta_{i, GY}$ and $\sigma_{i, GY}$ are beta coefficient and standard error, respectively. The P -value was based on Student's t distribution, where the degrees of freedom were determined by the number of SNPs included in the instrument for the trait of interest. We calculated Pearson's correlations between each pair of wPRSs in the control data before and after removal of pleiotropic SNPs. Egger's regression, as described in Bowden *et al.*,²⁵ was performed to detect potential pleiotropy of our instruments. We also included all instruments in the same model to evaluate possible independent associations of each instrument with breast cancer risk.

Associations of wPRSs with breast cancer risk were evaluated separately in the iCOGs and OncoArray datasets by treating these scores as continuous variables. A logistic regression was performed with age at interview/diagnosis, study site/country and PCs as covariates. The results were then combined using meta-analyses in METAL with a fixed-effects model.²⁶ We performed additional analyses adjusting for certain known breast cancer risk factors listed in Supplementary Table 1, available as Supplementary data at *IJE* online. Finally, we conducted subanalyses by estrogen receptor (ER) status, age at interview/diagnosis (< 50 versus ≥ 50), menopausal status at interview/breast cancer diagnosis

and family history of breast cancer. All statistical analyses were conducted using R statistical software (version 3.1.2).

Results

Approximately 90% of cases included in this study were diagnosed at age 40 or above. A total of 278 SNPs were selected to construct the instruments, for which the number of SNPs for each trait ranged from 4 to 166 (Table 1). The variance of each trait explained by its associated variants ranged from 0.23% for 2-h glucose to 2.89% for BMI (Table 1).

Using data from DIAGRAM, we demonstrated that all genetic instruments were associated with risk of type 2 diabetes in the direction that would be expected (Table 2). The strongest association was observed for the genetic instrument for fasting glucose (OR = 6.37, $P = 5.77 \times 10^{-16}$ and OR = 4.32, $P = 1.12 \times 10^{-11}$ before and after the exclusion of pleiotropic SNPs, respectively).

Removing pleiotropic SNPs did not appreciably change the associations of instruments with breast cancer risk (Table 3). A 1-SD increase in genetically predicted 2-h glucose levels was associated with an 80% increased risk of breast cancer (OR = 1.80, 95% CI = 1.30-2.49, $p = 4.02$

Table 1. Summary of instrument variables for obesity and glucose/insulin-related traits used in the current study

Traits	All SNPs			After exclusion of pleiotropic SNPs		
	No. of variants	Variance explained (%)	F statistics	No. of variants	Variance explained (%)	F statistics
2-h glucose	9	0.56	114.9	4 ^a	0.23	105.7
Fasting glucose	36	2.42	125.7	31 ^b	2.30	107.7
Fasting insulin	18	0.59	60.4	10 ^c	0.27	53.9
BMI	166	2.89	32.6	162 ^d	2.84	32.3
WHR _{adj} BMI	54	1.96	67.5	50 ^d	1.79	65.2

^aExcluding SNPs (or their correlated SNPs with $r^2 > 0.8$) associated with fasting glucose, fasting insulin, BMI and WHR_{adj} BMI.

^bExcluding SNPs (or their correlated SNPs with $r^2 > 0.8$) associated with levels of 2-h glucose, fasting insulin, BMI and WHR_{adj} BMI.

^cExcluding SNPs (or their correlated SNPs with $r^2 > 0.8$) associated with levels of 2-h glucose, fasting glucose, BMI and WHR_{adj} BMI.

^dExcluding SNPs (or their correlated SNPs with $r^2 > 0.8$) associated with levels of 2-h glucose, fasting glucose and fasting insulin.

Table 2. Associations of obesity and glucose/insulin-related traits with type 2 diabetes using data from DIAGRAM: results from Mendelian randomization analysis

Traits	All SNPs			After exclusion of pleiotropic SNPs		
	IV	OR (95% CI)	P	IV	OR (95% CI)	P
2-h glucose ^a	9	12.0 (6.90–21.0)	2.11×10^{-5}	4	21.5 (5.76–80.3)	0.005
Fasting glucose ^a	36	6.37 (4.87–8.32)	5.77×10^{-16}	31	4.32 (3.26–5.73)	1.12×10^{-11}
Fasting insulin ^a	18	1.92 (1.10–3.35)	0.024	10	4.62 (1.82–11.7)	0.005
BMI	132	1.92 (1.64–2.25)	2.86×10^{-13}	128	2.37 (1.99–2.82)	2.40×10^{-17}
WHR _{adj} BMI	53	1.87 (1.53–2.29)	5.93×10^{-8}	49	1.99 (1.61–2.46)	3.52×10^{-8}

^aORs calculated based on 1-SD increase in levels of genetically predicted 2-h glucose (2 mmol/L,²²), fasting glucose (0.65 mmol/L,¹⁷) and fasting insulin (0.60 ln[pmol/L]¹⁷).

Table 3. Associations of genetically predicted obesity and glucose/insulin-related traits with breast cancer risk: results from Mendelian randomization analysis

Traits	All SNPs				After exclusion of pleiotropic SNPs			
	OR	95% CI	P	P_{het}	OR	95% CI	P	P_{het}
2-h glucose ^a	1.50	1.21–1.86	2.13×10^{-4}	0.608	1.80	1.30–2.49	4.02×10^{-4}	0.566
Fasting glucose ^a	1.06	0.95–1.17	0.291	0.543	1.02	0.91–1.14	0.749	0.357
Fasting insulin ^a	1.16	0.96–1.41	0.128	0.939	1.71	1.26–2.31	5.09×10^{-4}	0.442
BMI								
per five-unit ^b	0.70	0.65–0.76	5.25×10^{-22}	0.042	0.70	0.66–0.77	5.05×10^{-19}	0.086
per SD ^a	0.76	0.72–0.80	5.25×10^{-22}	0.042	0.77	0.73–0.82	5.05×10^{-19}	0.086
WHR _{adj BMI} ^a	0.85	0.79–0.91	4.48×10^{-6}	0.132	0.85	0.79–0.91	9.22×10^{-6}	0.152

^aORs calculated based on 1-SD increase in levels of genetically predicted 2-h glucose (2 mmol/L,²²), fasting glucose (0.65 mmol/L,¹⁷), fasting insulin (0.60 ln[pmol/L],¹⁷), BMI and WHR_{adj BMI}.

^bORs calculated based on 5-unit increase of genetically predicted BMI (see Methods).

$\times 10^{-4}$). An inverse association was observed for both genetically predicted BMI and WHR_{adj BMI} (per five units of BMI increase: OR = 0.70, 95% CI = 0.66–0.77, $P = 5.05 \times 10^{-19}$; per unit increase of genetic risk score for WHR_{adj BMI}: OR = 0.85, 95% CI = 0.79–0.91, $P = 9.22 \times 10^{-6}$). The association of breast cancer risk with genetically predicted fasting insulin became significant after excluding pleiotropic SNPs (OR = 1.71, 95% CI = 1.26–2.31, $P = 5.09 \times 10^{-4}$). No association was observed for genetically predicted fasting glucose. Results of iCOGS and OncoArray are shown separately in [Supplementary Table 3](#), available as [Supplementary data](#) at *IJE* online.

Genetically predicted fasting insulin was correlated with both genetically predicted 2-h glucose and WHR_{adj BMI} ([Supplementary Table 4](#), available as [Supplementary data](#) at *IJE* online). Exclusion of pleiotropic SNPs attenuated these correlations. Mutual adjustment of all instruments did not materially change the observed associations with breast cancer risk described above ([Supplementary Table 5](#), available as [Supplementary data](#) at *IJE* online). We evaluated the associations of genetically predicted obesity and glucose/insulin-related traits with traditional risk factors for breast cancer and found that genetically predicted fasting insulin and WHR_{adj BMI} were associated with BMI in controls. Further, genetically predicted BMI was correlated with age at menarche, age at first live birth and breastfeeding history ([Supplementary Table 6](#), available as [Supplementary data](#) at *IJE* online). Adjusting for these covariates did not materially change the observed associations of genetically predicted fasting insulin, BMI and WHR_{adj BMI} with breast cancer risk ([Supplementary Table 7](#), available as [Supplementary data](#) at *IJE* online). Finally, using Egger's regression, we found that the intercept in the model was noticeable for genetically predicted 2-h glucose, BMI and WHR_{adj BMI}, indicating a strong

pleiotropic effect for these instruments ($P < 0.005$ for β_0 , [Supplementary Table 8](#), available as [Supplementary data](#) at *IJE* online).²⁵ No apparent pleiotropy was found for genetically predicted fasting insulin. The Mendelian randomization estimates from Egger's regression remained significant after accounting for detected pleiotropy for genetically predicted BMI and WHR_{adj BMI} ([Supplementary Table 8](#), available as [Supplementary data](#) at *IJE* online).

Stratified analysis was performed by age, menopausal status, ER status and family history of breast cancer. Genetically predicted 2-h glucose, BMI and WHR_{adj BMI} were consistently associated with breast cancer across all strata ([Figure 1A, C and D](#), $P_{\text{het}} > 0.05$, exclusion of pleiotropic SNPs). The association with genetically predicted fasting insulin was restricted to ER(+) cancer ([Figure 1B](#), $P_{\text{het}} 0.007$, exclusion of pleiotropic SNPs). The results of stratified analysis are shown for other sets of instrumental variables in [Supplementary Figures 1](#) (inclusion of pleiotropic SNPs) and [2](#) (fasting glucose, exclusion of pleiotropic SNPs), available as [Supplementary data](#) at *IJE* online.

Discussion

In this large study, we found that genetically predicted obesity, 2-h glucose and fasting insulin were associated with breast cancer risk. Measured BMI has been well established to be positively associated with breast cancer risk in postmenopausal women but inversely related to the risk in premenopausal women. Results from epidemiological studies investigating the association of breast cancer risk with WHR, fasting insulin and glucose have been inconsistent. Traditional epidemiological studies are prone to biases, including confounding, selection biases, recall biases and reverse causality. Mendelian randomization analyses take advantage of the random assignment of

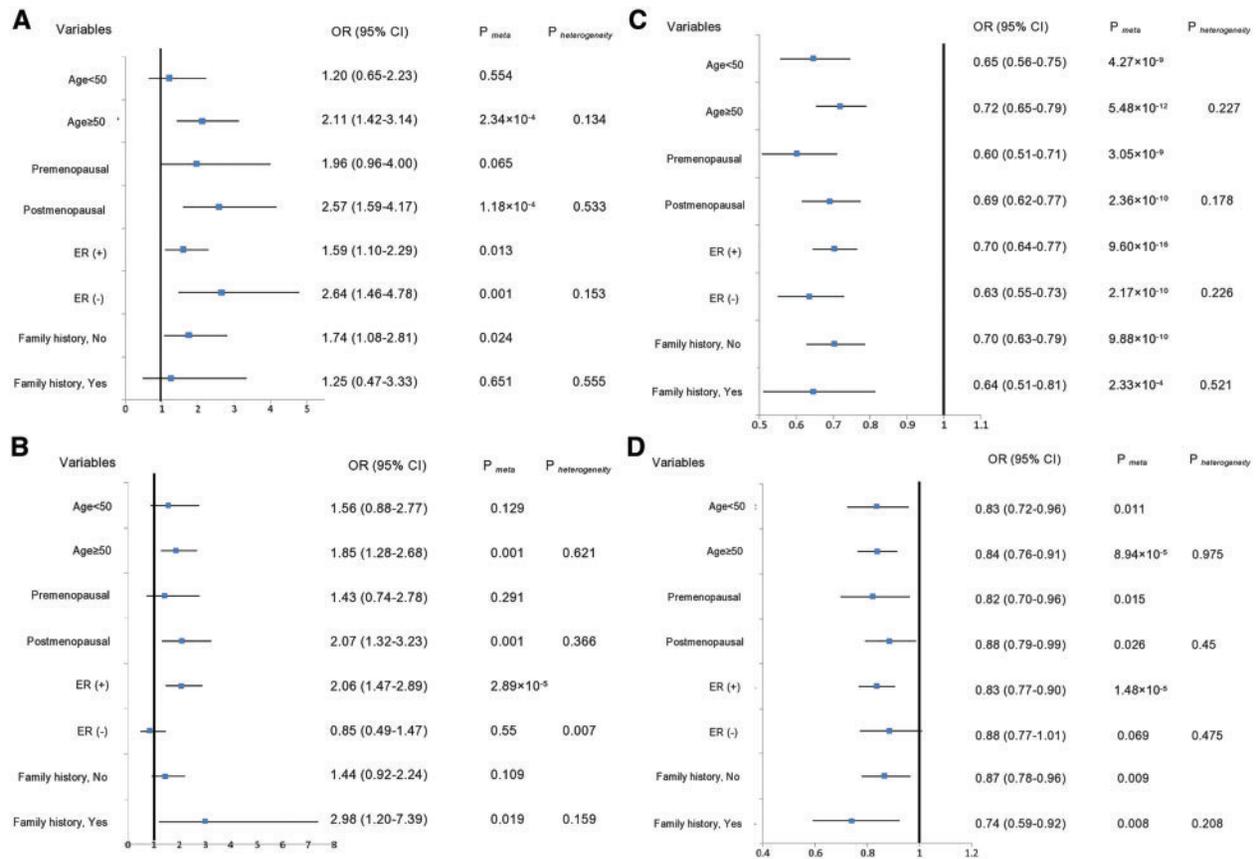


Figure 1. Associations of genetically predicted obesity and levels of circulating glucose and insulin with overall breast cancer risk: stratified analysis. The $P_{heterogeneity}$ was obtained from heterogeneity test across strata.

genetic alleles during gamete formation to minimize the biases commonly encountered in traditional epidemiological studies. When instrumental variables are not associated with any potential confounders and are not linked to the outcome via any alternative pathway, Mendelian randomization analysis using such instrumental variables resemble randomized clinical trials, and thus could provide strong results for causal inference for the exposure of interest.¹⁰

We found that the risk of breast cancer increased approximately 70% for each 1-SD increase of genetically predicted fasting insulin levels. Previous epidemiological studies were unable to reach a conclusion regarding the association between fasting insulin and breast cancer risk. A meta-analysis reported a null association for fasting insulin.⁸ However the I^2 , an indicator of heterogeneity across studies, was considerable. Our results provide strong evidence to support a positive association. Insulin is an important growth factor with cancer-promoting features such as stimulating cell mitosis and migration and inhibiting apoptosis. Its mitogenic effects involve the activation of Ras and the mitogen-activated protein kinase pathway,²⁷ of which the role in cancer development has been recognized.²⁸ Further, insulin may inhibit the production of sex

hormone-binding globulin and lead to elevated bioavailable estrogen levels.²⁹ It also has been shown that knock-down of insulin and IGF-1 receptors inhibits hormone-dependent growth of ER(+) breast cancer cells.³⁰ This may explain the association of fasting insulin with ER(+) breast cancer observed in this study.

Previous epidemiological studies have suggested that fasting glucose may be a risk factor for breast cancer, but few have assessed 2-h glucose levels, as the latter are difficult to investigate in large prospective cohort studies. Overall, a meta-analysis of prospective studies showed no strong evidence to support an association of fasting glucose levels and risk of breast cancer in non-diabetic women.⁹ In the current study, we found a positive association with breast cancer for genetically predicted 2-h glucose levels but not for fasting glucose. Although fasting glucose and 2-h glucose are closely correlated,³¹ they represent different biological processes. The genetically determined fasting glucose levels primarily reflect the glycogenolysis activity in liver and hepatic insulin sensitivity.³² On the other hand, the levels of post-challenge glucose are mainly determined by the amount and pace of insulin released into blood stream in response to the challenge as well as by the

glucose uptake in skeletal muscle cells (in other words, it primarily reflects beta cell function and skeletal muscle insulin sensitivity³³). The reasons why genetically predicted 2-h glucose, but not fasting glucose, is associated with increased risk of breast cancer are not clear. One animal study has provided evidence that transgenic mice with inactivated insulin and IGF-1 receptors in skeletal muscles (impaired skeletal muscle insulin sensitivity) can manifest hyperinsulinaemia and an accelerated development of breast cancer.³⁴ Since genetically predicted 2-h glucose is correlated with instruments for other traits, we cannot completely rule out the possibility that the association of 2-h glucose may be mediated by other insulin-related traits; even these traits were carefully adjusted, and pleiotropic SNPs were excluded in our analyses.

We reported previously that genetically predicted BMI was inversely associated with breast cancer risk in both pre- and postmenopausal women.³⁵ We have now confirmed this finding with a much larger sample size and more BMI-associated SNPs. Whereas our finding for premenopausal breast cancer is consistent with previous observational studies, the inverse association observed in our study between genetically predicted BMI and postmenopausal breast cancer risk contradicts previous findings based on measured BMI. Multiple lines of evidence suggest that early life body size may be inversely associated with both premenopausal and postmenopausal breast cancer risk.^{36,37} It has been speculated that reduced serum estradiol and progesterone levels, due to an increased frequency of anovulation, play a role. In addition, the association is further supported by the observation that early life fatness was inversely correlated with IGF-1 levels measured in later adulthood.³⁸ We hypothesize that genetically predicted BMI may be more closely correlated to early life body weight, and obesity determined using measured BMI later in life may be more closely related to environmental and lifestyle factors that are associated with breast cancer risk. Indeed, one previous study found that a BMI-genetic score was positively associated with weight gain before reaching middle age but inversely associated with weight gain after reaching middle age.³⁹ If the hypothesis is correct, our study may provide additional support for preventing weight gain later in life to reduce the risk of breast cancer.

Results from previous studies regarding the association of WHR with breast cancer risk have been inconsistent. Although several previous studies reported that measured WHR was associated with breast cancer risk,⁴⁰ we recently found that this association was substantially attenuated after adjusting for BMI using data from a large prospective cohort study conducted among Chinese women.⁴¹ In the current study, we observed an inverse association between genetically predicted $\text{WHR}_{\text{adj BMI}}$ and breast cancer risk in both

pre- and postmenopausal women. This finding was unexpected, given the close association of measured WHR with type 2 diabetes.⁴² As discussed previously for the BMI findings, we hypothesize that genetically predicted $\text{WHR}_{\text{adj BMI}}$ may reflect visceral adipose tissue level in early life, whereas measured WHR in late adulthood may reflect accumulation of visceral fats later in life. Additional research is needed to understand the inter-relationship of genetically predicted WHR, measured WHR and breast cancer risk.

We showed that genetically predicted obesity and circulating insulin and glucose levels were positively correlated with risk of type 2 diabetes. Epidemiological studies have shown that a previous diagnosis of type 2 diabetes was related to an elevated risk of breast cancer risk, although the association was weak to moderate.⁴³ However, in a previous study, we found a null association between a polygenic risk score for type 2 diabetes and breast cancer risk.⁴⁴ It is possible that lifestyle changes after diabetes diagnosis and/or diabetes treatment may have confounded this association. Given the significant association we found in this study for breast cancer risk with genetically predicted fasting insulin and 2-h glucose, two factors that are strongly associated with type 2 diabetes risk, we suggest that type 2 diabetes may be associated with breast cancer risk.

The sample size of our study is very large, providing us sufficient statistical power for Mendelian randomization analyses of multiple obesity, glucose/insulin-related traits and breast cancer risk. Our ability to perform Mendelian randomization analysis is limited by the genetic variants identified to date in GWAS, and the variance explained by these genetic variants for some traits is small. We used 10 instruments in our main analysis, which could lead to false-positive findings due to multiple comparisons. However, the associations reported in this study for 2-h glucose, fasting insulin, BMI and $\text{WHR}_{\text{adj BMI}}$ were robust, reaching the stringent Bonferroni corrected significance level ($P < 0.05/10 = 0.005$). Pleiotropy was found for the associations of obesity, but it is not likely that the observed associations can be primarily explained by pleiotropic effects.

In summary, this study provided new evidence that genetically predicted fasting insulin, 2-h glucose, BMI and $\text{WHR}_{\text{adj BMI}}$ are associated with breast cancer risk in women. Further research into the complex association of genetics, obesity, glucose/insulin-related traits and breast cancer risk will help to improve the understanding of underlying biological mechanisms for the associations observed in this study and may provide tools to reduce breast cancer risk.

Supplementary Data

Supplementary data are available at *IJE* online.

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References

- Bhaskaran K, Douglas I, Forbes H, dos-Santos-Silva I, Leon DA, Smeeth L. Body-mass index and risk of 22 specific cancers: a population-based cohort study of 5.24 million UK adults. *Lancet* 2014;**384**:755–65.
- Harvie M, Hooper L, Howell AH. Central obesity and breast cancer risk: a systematic review. *Obes Rev* 2003;**4**: 157–73.
- Kahn BB, Flier JS. Obesity and insulin resistance. *J Clin Invest* 2000;**106**:473–81.
- Stolzenberg-Solomon RZ, Graubard BI, Chari S *et al.* Insulin, glucose, insulin resistance, and pancreatic cancer in male smokers. *JAMA* 2005;**294**:2872–78.
- Albanes D, Weinstein SJ, Wright ME *et al.* Serum insulin, glucose, indices of insulin resistance, and risk of prostate cancer. *J Natl Cancer Inst* 2009;**101**:1272–79.
- Giovannucci E. Metabolic syndrome, hyperinsulinemia, and colon cancer: a review. *Am J Clin Nutr* 2007;**86**:s836–42.
- Pollak M. Insulin and insulin-like growth factor signalling in neoplasia. *Nat Rev Cancer* 2008;**8**:915–28.
- Hernandez AV, Guarnizo M, Miranda Y *et al.* Association between insulin resistance and breast carcinoma: a systematic review and meta-analysis. *PLoS One* 2014;**9**:e99317.
- Boyle P, Koechlin A, Pizot C *et al.* Blood glucose concentrations and breast cancer risk in women without diabetes: a meta-analysis. *Eur J Nutr* 2013;**52**:1533–40.
- Burgess S, Butterworth A, Thompson SG. Mendelian randomization analysis with multiple genetic variants using summarized data. *Genet Epidemiol* 2013;**37**:658–65.
- Burgess S, Small DS, Thompson SG. A review of instrumental variable estimators for Mendelian randomization. *Stat Methods Med Res* 2017;**26**:2333–55.
- Michailidou K, Hall P, Gonzalez-Neira A *et al.* Large-scale genotyping identifies 41 new loci associated with breast cancer risk. *Nat Genet* 2013;**45**:353–61, 361e1-2.
- Michailidou K, Lindstr m S, Dennis J *et al.* Association analysis identifies 65 new breast cancer risk loci. *Nature* 2017;**551**:92–94.
- Howie B, Fuchsberger C, Stephens M, Marchini J, Abecasis GR. Fast and accurate genotype imputation in genome-wide association studies through pre-phasing. *Nat Genet* 2012;**44**:955–59.
- Welter D, MacArthur J, Morales J *et al.* The NHGRI GWAS Catalog, a curated resource of SNP-trait associations. *Nucleic Acids Res* 2014;**42**:D1001–06.
- Scott RA, Lagou V, Welch RP *et al.* Large-scale association analyses identify new loci influencing glycemic traits and provide insight into the underlying biological pathways. *Nat Genet* 2012;**44**:991–1005.
- Nead KT, Sharp SJ, Thompson DJ *et al.* Evidence of a causal association between insulinemia and endometrial cancer: a Mendelian randomization analysis. *J Natl Cancer Inst* 2015;**107**. doi: 10.1093/jnci/djv178. [Epub ahead of print.]
- Locke AE, Kahali B, Berndt SI *et al.* Genetic studies of body mass index yield new insights for obesity biology. *Nature* 2015;**518**: 197–206.
- Turcot V, Lu Y, Highland HM *et al.* Protein-altering variants associated with body mass index implicate pathways that control energy intake and expenditure in obesity. *Nat Genet* 2018;**50**:26–41.
- Staiger D, Stock JH. Instrumental variables regression with weak instruments. *Econometrica* 1997;**65**:557–86.
- Burgess S, Thompson SG; CRP CHD Genetics Collaboration. Avoiding bias from weak instruments in Mendelian randomization studies. *Int J Epidemiol* 2011;**40**:755–64.
- Wareham NJ, Wong MY, Day NE. Glucose intolerance and physical inactivity: the relative importance of low habitual energy expenditure and cardiorespiratory fitness. *Am J Epidemiol* 2000;**152**:132–39.
- Shungin D, Winkler TW, Croteau-Chonka DC *et al.* New genetic loci link adipose and insulin biology to body fat distribution. *Nature* 2015;**518**:187–96.
- Morris AP, Voight BF, Teslovich TM *et al.* Large-scale association analysis provides insights into the genetic architecture and pathophysiology of type 2 diabetes. *Nat Genet* 2012;**44**:981–90.
- Bowden J, Davey Smith G, Burgess S. Mendelian randomization with invalid instruments: effect estimation and bias detection through Egger regression. *Int J Epidemiol* 2015;**44**:512–25.
- Willer CJ, Li Y, Abecasis GR. METAL: fast and efficient meta-analysis of genomewide association scans. *Bioinformatics* 2010;**26**:2190–91.
- Draznin B. Mitogenic action of insulin: friend, foe or ‘frenemy’? *Diabetologia* 2010;**53**:229–33.

28. Dhillon AS, Hagan S, Rath O, Kolch W. MAP kinase signalling pathways in cancer. *Oncogene* 2007;26:3279–90.
29. Daka B, Rosen T, Jansson PA, Råstam L, Larsson CA, Lindblad U. Inverse association between serum insulin and sex hormone-binding globulin in a population survey in Sweden. *Endocr Connect* 2013;2:18–22.
30. Fox EM, Miller TW, Balko JM *et al.* A kinome-wide screen identifies the insulin/IGF-I receptor pathway as a mechanism of escape from hormone dependence in breast cancer. *Cancer Res* 2011;71:6773–84.
31. Ito C, Maeda R, Ishida S, Sasaki H, Harada H. Correlation among fasting plasma glucose, two-hour plasma glucose levels in OGTT and HbA1c. *Diabetes Res Clin Pract* 2000;50:225–30.
32. Matthews DR, Hosker JP, Rudenski AS, Naylor BA, Treacher DF, Turner RC. Homeostasis model assessment: insulin resistance and beta-cell function from fasting plasma glucose and insulin concentrations in man. *Diabetologia* 1985;28:412–19.
33. DeFronzo RA, Tripathy D. Skeletal muscle insulin resistance is the primary defect in type 2 diabetes. *Diabetes Care* 2009;32(Suppl 2):S157–63.
34. Novosyadlyy R, Lann DE, Vijayakumar A *et al.* Insulin-mediated acceleration of breast cancer development and progression in a nonobese model of type 2 diabetes. *Cancer Res* 2010;70:741–51.
35. Guo Y, Warren Andersen S, Shu X-O *et al.* Genetically predicted body mass index and breast cancer risk: Mendelian randomization analyses of data from 145,000 women of European descent. *PLoS Med* 2016;13:e1002105.
36. Baer HJ, Tworoger SS, Hankinson SE, Willett WC. Body fatness at young ages and risk of breast cancer throughout life. *Am J Epidemiol* 2010;171:1183–94.
37. Baer HJ, Colditz GA, Rosner B *et al.* Body fatness during childhood and adolescence and incidence of breast cancer in premenopausal women: a prospective cohort study. *Breast Cancer Res* 2005;7:R314–25.
38. Poole EM, Tworoger SS, Hankinson SE, Schernhammer ES, Pollak MN, Baer HJ. Body size in early life and adult levels of insulin-like growth factor 1 and insulin-like growth factor binding protein 3. *Am J Epidemiol* 2011;174:642–51.
39. Rukh G, Ahmad S, Ericson U *et al.* Inverse relationship between a genetic risk score of 31 BMI loci and weight change before and after reaching middle age. *Int J Obes* 2016;40:252–59.
40. Kyrgiou M, Kalliala I, Markozannes G *et al.* Adiposity and cancer at major anatomical sites: umbrella review of the literature. *BMJ* 2017;356:j477.
41. Liu Y, Warren Andersen S, Wen W *et al.* Prospective cohort study of general and central obesity, weight change trajectory and risk of major cancers among Chinese women. *Int J Cancer* 2016;139:1461–70.
42. Kodama S, Horikawa C, Fujihara K *et al.* Comparisons of the strength of associations with future type 2 diabetes risk among anthropometric obesity indicators, including waist-to-height ratio: a meta-analysis. *Am J Epidemiol* 2012;176:959–69.
43. Boyle P, Boniol M, Koechlin A *et al.* Diabetes and breast cancer risk: a meta-analysis. *Br J Cancer* 2012;107:1608–17.
44. Zhao Z, Wen W, Michailidou K *et al.* Association of genetic susceptibility variants for type 2 diabetes with breast cancer risk in women of European ancestry. *Cancer Causes Control* 2016;27:679–93.