Diabetologia
DOI 10.1007/s00125-010-1710-3

ARTICLE

Anthropometric measures and glucose levels in a large multi-ethnic cohort of individuals at risk of developing type 2 diabetes

L. de Koning · H. C. Gerstein · J. Bosch · R. Diaz · V. Mohan · G. Dagenais · S. Yusuf · S. S. Anand · for the EpiDREAM Investigators

Received: 13 November 2009 / Accepted: 2 February 2010

Abstract

Aims/hypotheses We determined: (1) which of BMI, waist circumference, hip circumference and WHR has the strongest association and explanatory power for newly diagnosed type 2 diabetes and glucose status; and (2) the impact of considering two measures simultaneously. We also explored variation in anthropometric associations by sex and ethnicity.

Methods We performed cross-sectional analysis of 22,293 men and women who were from five ethnic groups and 21 countries, and at risk of developing type 2 diabetes. Standardised anthropometric associations with type 2 diabetes and AUC of glucose status from OGTT (AUC_{OGTT}) were determined using multiple regression. Explanatory power was assessed using the c-statistic and adjusted r^2.

Results An increase in BMI, waist circumference or WHR had similar positive associations with type 2 diabetes, AUC_{OGTT} and explanatory power after adjustment for age, sex, smoking and ethnicity ($p<0.01$). However, using BMI and WHR together resulted in greater explanatory power than with other models ($p<0.01$). Associations were strongest when waist circumference and hip circumference were used together, a combination that had greater explanatory power than other models except for BMI and WHR together ($p<0.01$). Results were directionally similar according to sex and ethnicity; however, significant variations in associations were observed among these subgroups.

Conclusions/interpretation The combination of BMI and WHR, or of waist circumference and hip circumference has the best explanatory power for type 2 diabetes and glucose status compared with a single anthropometric measure. Measurement of waist circumference and hip circumference is required to optimally identify people at risk of type 2 diabetes and people with elevated glucose levels.

Keywords Anthropometric measures · Ethnicity · Oral glucose tolerance test · Type 2 diabetes

Electronic supplementary material The online version of this article (doi:10.1007/s00125-010-1710-3) contains supplementary material, which is available to authorised users.

L. de Koning · H. C. Gerstein · J. Bosch · S. Yusuf · S. S. Anand
The Population Health Research Institute, McMaster University,
Hamilton, ON, Canada

H. C. Gerstein · S. Yusuf · S. S. Anand
The Department of Medicine, McMaster University,
Hamilton, ON, Canada

L. de Koning · H. C. Gerstein · J. Bosch · S. Yusuf · S. S. Anand
The Department of Clinical Epidemiology and Biostatistics,
McMaster University,
Hamilton, ON, Canada

R. Diaz
Instituto Cardiovascular de Rosario,
Rosario, Argentina

V. Mohan
Dr Mohan's Diabetes Specialties Center and Madras Diabetes Research Foundation,
Chennai, India

G. Dagenais
Québec Heart Institute, Institut Universitaire de Cardiologie et de Pneumologie, Université Laval,
Québec, QC, Canada

H. C. Gerstein · J. Bosch · S. Yusuf · S. S. Anand (✉)
David Braley Cardiac, Vascular and Stroke Research Institute,
Hamilton General Hospital Campus, 237 Barton Street East,
Hamilton, ON L8L 2X2, Canada
e-mail: anands@mcmaster.ca

Published online: 07 April 2010

Abbreviations

AUC_{OGTT}	AUC of glucose status
DREAM	Diabetes Reduction Assessment with Ramipril and Rosiglitazone Medication
EpiDREAM	Epidemiological arm of the DREAM study

Introduction

Type 2 diabetes mellitus is a major risk factor for blindness, limb amputation, cardiovascular disease and death. Among the preventable risk factors for type 2 diabetes, overweight (BMI ≥25 kg/m^2) and obesity (BMI≥30 kg/m^2) are regarded as the most important [1]. Currently more than 2 billion people over the age of 15 in the world (~29% of total population) are overweight or obese, a figure expected to rise to over 3 billion (~40%) by 2030 [2, 3]. Most of this increase will occur in low-income countries where sedentary lifestyles and high-energy diets are being adopted [1]. By 2030, the prevalence of type 2 diabetes is projected to rise to 7.3%, afflicting over 380 million people worldwide [4, 5].

Traditionally, BMI has been used to define overweight and obesity, and is predictive of cardiometabolic risk including incident type 2 diabetes [6] and cardiovascular events such as myocardial infarction [7]. However, BMI has some limitations. First, it does not distinguish between individuals with high muscle mass, excess fat or abdominal obesity. A preponderance of abdominal and visceral fat is strongly associated with insulin resistance, type 2 diabetes and high lipids [8]. Recently, in a large international case–control study, measures of abdominal obesity (waist circumference and WHR) were more strongly associated with myocardial infarction than BMI [7]. Second, BMI may not be appropriate to use in all individuals, as the association of BMI with cardiometabolic risk seems to vary according to sex [9, 10] and ethnicity [6, 11, 12].

The primary objective of this investigation was to determine which of the anthropometric measures BMI, waist circumference, hip circumference and WHR has the strongest association and best explanatory power for glucose levels in a large, ethnically diverse cohort of individuals at risk of developing type 2 diabetes. The second objective was to measure the impact of considering an additional anthropometric measure. The third was to explore whether associations differ by sex and ethnicity.

Methods

Written consent was obtained from all participants prior to initiating this study, which was approved by the Ethics Committees at participating institutions. The study complied with the declaration of Helsinki. Between July 4 2001 and August 15 2003, 24,595 men and women aged 30 years or over at 191 centres from 21 countries (Electronic supplementary material [ESM] Table 1) were screened for entry into the Diabetes Reduction Assessment with Ramipril and Rosiglitazone Medication (DREAM) trial [13]. Clinical centres screened individuals who had an increased risk of type 2 diabetes as defined by family history, ethnicity, gestational diabetes and abdominal obesity. All individuals underwent an 8 h fast and a 75 g OGTT. On the basis of a single test, fasting venous plasma glucose ≥7.0 mmol/l (126 mg/dl) or a 2 h glucose ≥11.1 mmol/l (200 mg/dl) was defined as being compatible with a diagnosis of type 2 diabetes [14]. There were no inclusion criteria for BMI. Screened persons with impaired fasting glucose or impaired glucose tolerance were asked to participate in the DREAM trial [13]. Trial participants and non-participants became part of an epidemiological arm of DREAM called EpiDREAM, which is the cohort used for this analysis.

Anthropometric measures including weight (kg), height (m), waist circumference (cm) and hip circumference (cm) were taken using a standardised protocol. Standing height was measured to the nearest 0.1 cm with the participant looking straight ahead in bare feet and with his/her back against a wall. Weight was measured to the nearest 0.1 kg in light clothing. Waist and hip circumference were measured in duplicate using a non-flexible tape measure with an attached spring balance exerting a weight of 750 g. Waist circumference was assessed at the smallest diameter between the costal margin and iliac crest. Hip circumference was assessed at the level of the greater trochanters. Averages of the two measures were used in all analyses.

Information on ethnicity, medical history and smoking status was collected by self-administered questionnaire.

Statistical analysis For this analysis we excluded participants (n=1,847) who: (1) could not be assigned to one of five ethnic groups (Aboriginal, African, South Asian, European and Latin American); (2) had missing data (n=373); or (3) had been previously diagnosed with type 2 diabetes (n=82). This left 22,293 participants. Student's t test, one-way ANOVA and the χ^2 test were used to evaluate differences in participant characteristics. Simple linear and logistic regression were used to test for trends between anthropometric measures and participant characteristics.

Multiple logistic and linear regression were used to determine standardised (per 1 SD) associations of anthropometric measures (BMI, waist circumference, hip circumference, WHR) with type 2 diabetes and a continuous measure of glucose status defined as the AUC (line) of fasting and 2 h post-load plasma glucose values, i.e. AUC of glucose status (AUC_{OGTT}), which was calculated (mmol/l×h) as fasting+2 h glucose, after adjusting for age, sex, smoking status and ethnicity. To validate the use of the AUC_{OGTT}, we repeated our analyses using fasting and 2 h glucose levels separately.

Significant differences in standardised associations were defined to have occurred when the 95% CIs of ORs or beta coefficients did not overlap. We determined the model explanatory power for type 2 diabetes by calculating the c-statistic for receiver operating characteristic curves and used the Mann–Whitney test to test for differences between models arising from the same dataset [15]. Explanatory power for linear regression was evaluated using the adjusted R^2 statistic.

To determine the impact of considering an additional anthropometric measure on association strength and explanatory power, an extra term was included in the models. This was only done if the correlation between the two measures was less than 0.80. Models containing waist circumference or hip circumference with WHR were not tested because of difficulties in interpreting the coefficients. To test whether anthropometric associations were consistent across levels of the second measure, multiplicative terms were included in the models (e.g. waist circumference×hip circumference). To illustrate the effect of considering two measures simultaneously, measures were collapsed into thirds (tertiles), and ORs and AUC_{OGTT} levels were calculated for the nine categories. Analyses were repeated among men, women and ethnic groups.

To test for interactions with sex, multiplicative terms were included in the regression models (e.g. waist circumference× sex). To test for interactions with ethnicity, log-odds ratios and beta coefficients (adjusted for age, sex and smoking) were evaluated over the same interval (1 SD) and compared using Cochran's Q test for heterogeneity [16]. When there was significant ethnic heterogeneity, we defined significant intra-ethnic differences as occurring when the 95% CIs of ORs or beta coefficients did not overlap. SAS version 9.1 (SAS, Cary, NC, USA) and Microsoft Excel version 9.0 (Redmond, WA, USA) were used for all data analyses.

Results

Participant characteristics Participant characteristics are listed in Table 1. Of the 22,293 individuals, 60.0% were women and 47.1% were of non-white ethnicity. The prevalence of newly diagnosed type 2 diabetes was 14.0% and mean AUC_{OGTT} was 13.2 mmol/l×h. Mean AUC_{OGTT} among those with type 2 diabetes was significantly higher than in healthy participants (20.9 vs 12.0 mmol/l×h; $p<0.01$). Anthropometric measures were significantly and positively associated with type 2 diabetes and AUC_{OGTT}, as well as with age, male sex, smoking, African ethnicity and European ethnicity (data not shown; $p<0.01$ for trends). Anthropometric measures were significantly ($p<0.01$) correlated with each other (BMI with hip circumference $r=0.82$, waist circumference with hip circumference $r=0.76$, BMI with waist circumference $r=0.75$, waist circumference with WHR $r=0.57$, BMI with WHR $r=0.14$, hip circumference with WHR $r=-0.08$).

Adjusted associations of anthropometric measures with type 2 diabetes and AUC_{OGTT} Among individual metrics, an increase in BMI, waist circumference, hip circumference or WHR was associated with a significant increase in the odds of type 2 diabetes and AUC_{OGTT} after adjusting for age, sex, smoking and ethnicity (Fig. 1). The associations for hip circumference were significantly weaker. For type 2 diabetes, the model containing waist circumference had the highest explanatory power, which was significantly greater than the model containing BMI (Fig. 1a). Similarly, the model containing waist circumference had the highest explanatory power for AUC_{OGTT} (Fig. 1b).

Due to the high correlation between BMI and hip circumference ($r=0.82$), the only additional models that were tested included BMI+waist circumference, BMI+ WHR and waist circumference+hip circumference. Models containing BMI and WHR had the greatest explanatory power (T2D: $p<0.01$) (Fig. 1). Participants in the highest tertile combination of BMI and WHR had a fourfold greater odds of type 2 diabetes (AUC_{OGTT} 14.6 mmol/l×h) than participants in the lowest combination (AUC_{OGTT} 12.0 mmol/l×h) (Fig. 2a and c). Models containing waist circumference and hip circumference had higher explanatory power (T2D: $p<0.01$) than other models except those containing BMI and WHR (Fig. 1). Participants in the highest tertile of waist circumference and lowest tertile of hip circumference had a 2.25-fold higher odds of type 2 diabetes (AUC_{OGTT} 14.2 mmol/l×h) than those in the lowest tertile of waist circumference and highest tertile of hip circumference (AUC_{OGTT} 10.9 mmol/l×h) (Fig. 2b and d). Using BMI and waist circumference together had little impact on explanatory power; however, BMI associations were attenuated compared with waist circumference. Interactions between anthropometric measures in the same model (i.e. BMI×waist circumference, BMI×WHR, waist circumference×hip circumference) showed that associations with AUC_{OGTT} were slightly weaker at higher levels of the second measure ($p<0.03$) (Fig. 1). The associations between BMI and type 2 diabetes, and waist circumference and type 2 diabetes were somewhat reduced when at the higher level of the other measure ($p<0.01$).

Findings were similar for fasting glucose and 2 h glucose (ESM Table 2) among men, women and ethnic groups (data not shown).

Table 1 Characteristics of participants in EpiDREAM

Characteristic	Overall	Women	Men	Aboriginal	African	South Asian	European	Latin American
Per cent (*n*)	100 (22,293)	60.0 (13,374)	40.0 (8,919)	12.1 (2,697)	6.5 (1,458)	20.3 (4,535)	52.9 (11,795)	8.1 (1,808)
Age (years)	52.2 (11.4)	52.1 (11.3)	52.4 (11.5)	52.0 (11.6)	53.9 (11.0)	44.7 (9.2)	55.1 (10.8)	51.3 (11.4)
Post-menopausal women, % (*n*)	28.5 (5,054)	37.9 (5,054)		32.2 (799)	37.2 (406)	14.7 (563)	31.7 (2,799)	31.9 (487)
Smoker, % (*n*)[a]	44.3 (9,861)	36.6 (4,899)	55.6 (4,962)	55.4 (1,495)	37.5 (546)	15.8 (714)	52.8 (6,217)	49.1 (889)
Never smoked, % (*n*)	55.8 (12,432)	63.4 (8,475)	44.4 (3,957)	44.6 (1,202)	62.6 (912)	84.3 (3,821)	47.3 (5,578)	50.8 (919)
BMI (kg/m^2)	29.9 (6.2)	30.6 (6.6)	28.9 (5.3)	31.4 (6.2)	32.3 (7.0)	26.3 (4.5)	30.5 (6.1)	30.9 (6.0)
Obese, % (*n*)	42.8 (9,533)	47.6 (6,362)	35.6 (3,171)	53.3 (1,438)	57.6 (840)	17.6 (799)	47.0 (5,546)	50.3 (910)
Waist circumference (cm)	95.2 (14.4)	92.6 (14.4)	99.0 (13.4)	98.3 (14.6)	97.6 (14.5)	89.3 (11.2)	96.4 (14.9)	95.3 (13.6)
Hip circumference (cm)	106.8 (13.3)	108.6 (14.3)	104.1 (11.1)	109.6 (13.2)	111.4 (14.3)	100.1 (10.2)	108.1 (13.4)	107.0 (12.7)
WHR (units)	0.892 (0.089)	0.853 (0.080)	0.951 (0.068)	0.897 (0.086)	0.877 (0.077)	0.894 (0.082)	0.892 (0.095)	0.891 (0.084)
Type 2 diabetes, % (*n*)	14.0 (3,112)	12.3 (1,650)	16.4 (1,462)	9.9 (267)	18.2 (265)	14.1 (640)	14.5 (1712)	12.6 (228)
AUC_{OGTT} (mmol/l×h)	13.2 (4.3)	13.0 (3.9)	13.6 (4.7)	12.9 (3.8)	14.0 (4.7)	13.2 (5.4)	13.3 (3.8)	12.9 (4.0)

Values are means (SD) for continuous variables, unless otherwise indicated

[a] Current or previous smoker

All characteristics differed significantly by sex ($p<0.01$ *t* test); similarly, significant inter-ethnic differences were seen among all characteristics ($p<0.01$ ANOVA)

Aboriginal: Indigenous North American, Indigenous South American or Australian Aborigine; African: Black; South Asian: Indian, Sri Lankan, Pakistani, Bangladeshi; European: White; Latin American: Mixed European and Native South American

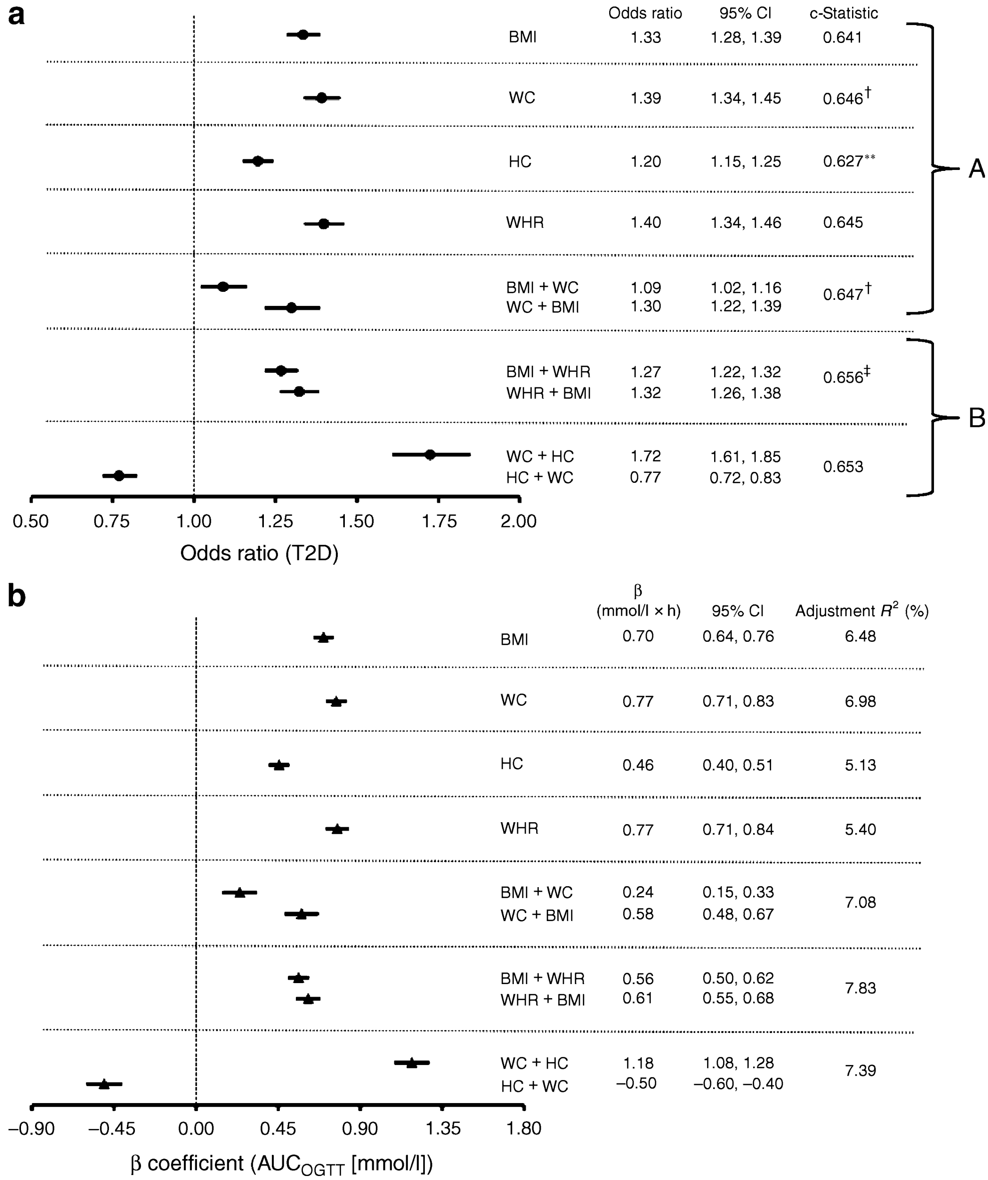


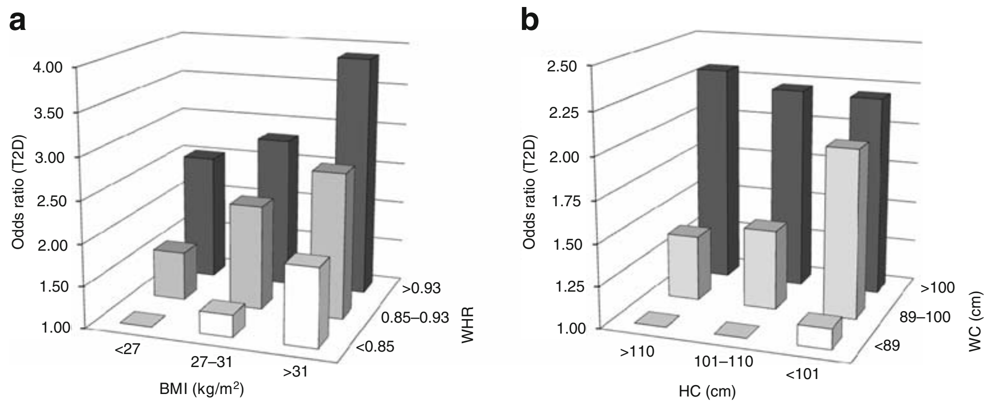
Fig. 1 Standardised associations of anthropometric measures with type 2 diabetes (**a**) and AUC_{OGTT} (**b**). Odds ratios (**a**) and beta coefficients (**b**) represent changes in the odds of type 2 diabetes (T2D) or AUC_{OGTT} for one SD increase in anthropometric measures independently of age, sex, smoking, ethnicity and other anthropometric measures. The + symbol indicates: additionally adjusted for anthropometric measure after symbol. SDs: BMI 6.2 kg/m^2, waist circumference (WC) 14.4 cm, hip circumference (HC) 13.3 cm, WHR 0.09. c-Statistic significantly higher for B than A (p<0.01). $^†p$<0.02 for c-statistic higher than model containing BMI alone; $^{**}p$<0.01 for c-statistic lower than model containing BMI alone; $^‡p$<0.02 for c-statistic higher than all models. Standardised beta coefficients and p values for interaction terms: (1) BMI × waist circumference: type 2 diabetes β=−0.06, p<0.01; AUC_{OGTT} β=−0.13 mmol/l × h, p<0.01; (2) BMI × WHR: type 2 diabetes β=−0.02, p=0.36; AUC_{OGTT} β=−0.05 mmol/l × h, p=0.03; and (3) WC × HC: type 2 diabetes β=−0.02, p=0.19; AUC_{OGTT} β=−0.04 mmol/l × h, p=0.03

Interactions with sex Significant interactions with sex were observed for waist circumference and hip circumference. For an equivalent increase in waist circumference, women had a significantly greater increase in the odds of type 2 diabetes than men (Table 2). In models containing waist circumference, an increase in hip circumference was associated with a greater decrease in the odds of type 2 diabetes among men. Results for AUC_{OGTT} were qualitatively similar (ESM Table 3).

Interactions with ethnicity Ethnic heterogeneity was identified among several BMI and hip circumference associations with type 2 diabetes (Fig. 3) and AUC_{OGTT} (data not shown). However there were few significant ethnic comparisons. In general, people of Aboriginal origin had the strongest associations of both BMI and hip circumference with type 2 diabetes and/or AUC_{OGTT}, whereas people of African origin had the weakest associations. Among Aboriginals, BMI, hip circumference and BMI adjusted for WHR were significantly more strongly associated with type 2 diabetes and AUC_{OGTT} than among Africans and South Asians. Associations between BMI and type 2 diabetes among Europeans were significantly stronger than among Africans.

Discussion

This investigation demonstrates that waist circumference and hip circumference are required to optimally identify people with elevated glucose levels in an ethnically diverse, high-risk population. The combination of BMI and WHR, or of waist circumference and hip circumference has the



c

WHR \ BMI (kg/m²)	<27	27–31	>31
<0.85	206 / 2,848 (12.0)	185 / 1,975 (12.5)	263 / 1,954 (13.3)
0.85–0.93	283 / 2,287 (12.3)	362 / 2,124 (13.0)	386 / 1,989 (13.5)
>0.93	320 / 1,485 (13.3)	504 / 2,285 (13.7)	603 / 2,234 (14.6)

d

WC (cm) \ HC (cm)	>110	101–110	<101
<89	32 / 354 (10.9)	166 / 1,853 (11.9)	503 / 4,545 (12.9)
89–100	215 / 1,642 (12.7)	478 / 3,150 (13.0)	362 / 1,615 (13.5)
>100	930 / 4,255 (14.0)	373 / 1,552 (13.9)	53 / 215 (14.2)

Fig. 2 Odds ratios for type 2 diabetes and mean AUC_{OGTT} levels by tertiles of anthropometric measures, stratified (**a**, **c**) by BMI and WHR, and (**b**, **d**) by waist circumference (WC) and hip circumference (HC). Type 2 diabetes (T2D) cases with non-cases are shown for tertiles as indicated (**c**, **d**). Mean AUC_{OGTT} levels are for 52-year-old, non-smoking European men. Data are presented as *n*/*n* (mean AUC_{OGTT} in mmol/l×h). All associations adjusted for age, sex, smoking and ethnicity

best explanatory power for type 2 diabetes and glucose status compared with a single anthropometric measure. These findings were generally consistent among men, women and different ethnic groups, although some sex- and ethnicity-related variations were observed.

Several studies have compared the associations of anthropometric measures with type 2 diabetes. In a meta-analysis of 32 prospective studies, BMI, waist circumference and WHR had associations with incident type 2 diabetes that were not significantly different [17]. In a review examining variation in the c-statistic (17 prospective studies, 35 cross-sectional studies), Qiao and Nyamdorj found that no measure had consistently higher explanatory power for type 2 diabetes risk [18]. In our study, BMI, waist circumference and WHR had nearly identical associations with type 2 diabetes and $AUC_{OGTT,}$ and similar explanatory power. However, associations and explanatory power changed when an extra measure was included in the models. For example, when BMI and WHR were included in the same model, associations with type 2 diabetes became weaker, whereas explanatory power rose significantly. This probably occurred because BMI and WHR both provide information for predicting type 2 diabetes and glucose status (general obesity, abdominal shape), and are

Table 2 Interactions of anthropometric measures and sex with type 2 diabetes

Measure	Men			Women			*p* value for interaction
	OR	95% CI	*p* value	OR	95% CI	*p* value	
BMI	1.33	1.25, 1.42	<0.01	1.34	1.28, 1.40	<0.01	0.97
WC	1.28	1.21, 1.37	<0.01	1.48	1.41, 1.54	<0.01	<0.01
HC	1.14	1.07, 1.22	<0.01	1.22	1.17, 1.28	<0.01	0.11
WHR	1.39	1.29, 1.50	<0.01	1.40	1.33, 1.48	<0.01	0.83
BMI+WC[a]	1.11	0.92, 1.35	0.27	1.23	1.06, 1.42	<0.01	0.26
WC+BMI[a]	1.22	1.13, 1.32	<0.01	1.39	1.28, 1.50	<0.01	<0.01
BMI+WHR[a]	1.21	1.13, 1.30	<0.01	1.29	1.23, 1.36	<0.01	0.12
WHR+BMI[a]	1.27	1.18, 1.37	<0.01	1.35	1.28, 1.43	<0.01	0.20
WC+HC[a]	1.58	1.46, 1.71	<0.01	1.87	1.73, 2.03	<0.01	<0.01
HC+WC[a]	0.67	0.61, 0.73	<0.01	0.80	0.74, 0.86	<0.01	<0.01

Odds ratios represent sex-specific changes in the odds of type 2 diabetes for one SD increase in anthropometric measures independently of age, smoking, ethnicity and other anthropometric measures

Standard deviations: BMI 6.2 kg/m^2, waist circumference (WC) 14.4 cm, hip circumference (HC) 13.3 cm, WHR 0.09

[a] Additionally adjusted for second term after +

Results for AUC_{OGTT} were qualitatively similar and are shown in ESM Table 2

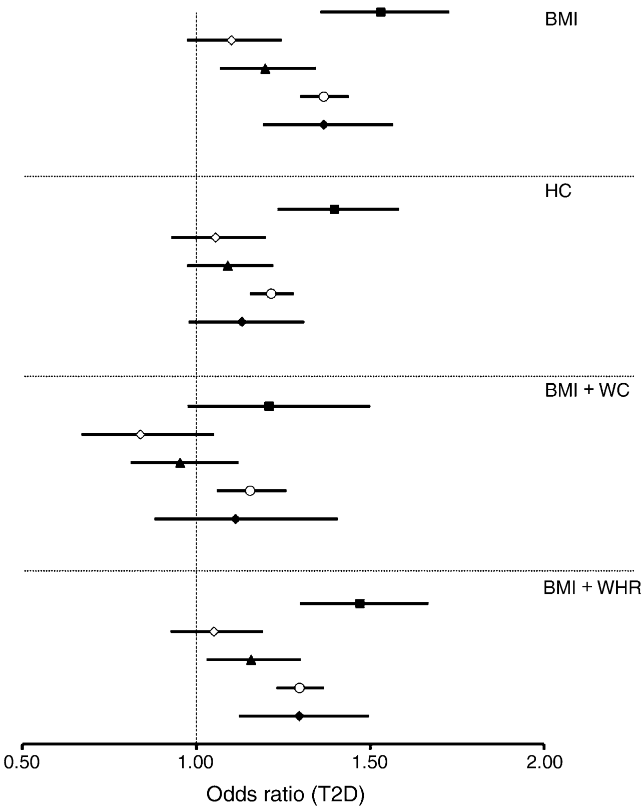


Fig. 3 Ethnic-specific standardised associations exhibiting significant overall ethnic heterogeneity by Cochran's Q test. Odds ratios represent changes in the odds of type 2 diabetes (T2D) for one SD increase in anthropometric measures independently of age, sex, smoking and other anthropometric measures. Standard deviations: BMI 6.2 kg/m^2, waist circumference (WC) 14.4 cm, hip circumference (HC) 13.3 cm, WHR 0.09. Results for AUC_{OGTT} were qualitatively similar. The + symbol indicates: additionally adjusted for anthropometric measure after symbol. Black squares, Aboriginal; white diamonds, African; triangles, South Asian; circles, European; black diamonds, Latin American

weakly correlated with each other (correlation of BMI with WHR r=0.14) [19].

When waist circumference and hip circumference were included in the same model, associations for waist circumference became significantly stronger and hip circumference was inversely associated with type 2 diabetes and glucose status. This was accompanied by a significant increase in explanatory power. Waist and hip circumference have opposite relationships with cardiometabolic risk. However, due to their high correlation (r=0.76 in EpiDREAM), these only become apparent after mutual adjustment [20–24]. Increased waist circumference is likely to be associated with cardiometabolic risk by the presence of visceral fat and is balanced by hip circumference, which is associated with leg muscularity, hip subcutaneous fat and oestrogen [23]. Use of WHR to control for this confounding may not be appropriate because absolute levels of waist and hip circumference can differ between individuals with the same WHR. This can result in misclassification if both waist and hip circumference are determinants of risk [25]. WHR also has lower correlations with visceral fat [26]. In our study, the model containing both waist and hip circumference had stronger associations as well greater explanatory power than the model containing WHR. However, waist and hip circumference together had significantly lower explanatory power than the model containing BMI and WHR, which may be due to the high correlation between waist circumference and hip circumference. Nevertheless, the simplest strategy to achieve a significant improvement in explanatory power is to use waist circumference and hip circumference rather than BMI and WHR. Using both waist and hip circumference does not require the collection of weight and height, or any calculation. Interestingly, the choice of two measures may be less critical among large individuals, as we observed a slight weakening of associations at higher levels of other anthropometric measures.

Our results indicate that an increase in waist circumference is associated with greater risk among women and that an increase in hip circumference is associated with a lower risk among men. While the mechanism behind these findings is unknown, women have lower muscle mass than men, so an increase in waist circumference could be associated with a proportionally greater increase in visceral fat compared with men. Also an equivalent amount of visceral fat in women is more strongly correlated with cardiometabolic risk than in men [27]. Another possibility is that a shift towards android obesity in women indicates a change in hormonal state as is observed in post-menopausal women and in women with polycystic ovarian syndrome or Turner's syndrome, which can elevate type 2 diabetes risk. Oestrogen replacement among post-menopausal women is associated with a lower incidence of type 2 diabetes [28, 29]. The reason for the interaction with sex with regard to hip circumference is unclear. Hip circumference captures a measure of muscularity in the gluteal region, so an increase in hip circumference could be associated with a greater increase in protective muscle mass in men than in women, as men are naturally more muscular than women. Interestingly, controlling for BMI did not change these results (data not shown).

We found some ethnic variation in the associations. In particular, BMI and hip circumference had the strongest associations among Aboriginal people and the weakest among Africans. However, differences among BMI associations disappeared after adjusting for waist circumference. Previous studies indicate that Africans possess greater lean muscle mass than other groups for the same BMI and that Aboriginal people are susceptible to visceral fat accumulation [30–33]. Therefore, an increase in BMI could reflect ethnic-specific changes in body composition. Several studies report ethnic differences in fat distribution and visceral fat content [12, 34, 35], which may explain ethnic differences in cardiometabolic risk [11, 12]. However we were not able to directly assess visceral fat in our study. Moreover, because the CIs overlapped for most associations, which were derived from the analysis of multiple subgroups, our results should be interpreted with caution.

Our study has several strengths. First, participants were sampled from 21 countries, with non-whites making up more than 50% of participants. Second, the sample size was large, allowing us to detect small differences in risk, which could be very important given the widespread use of anthropometric measures in type 2 diabetes risk assessment. Third, type 2 diabetes was newly detected and therefore participants could not have initiated behavioural (e.g. dietary) changes in response to a diagnosis of type 2 diabetes that might have altered anthropometric measurements and type 2 diabetes risk. Fourth, unlike meta-analytic comparisons of anthropometric measures, which make assumptions about the variation in measures across studies, we made comparisons in the same population.

Our study also has some limitations. The most important is that the EpiDREAM population is not a random sample, such that participant characteristics and associations reported by us may not be present in the general population. However, this analysis is internally valid and its results are clearly relevant to the substantial numbers of people at high risk of developing type 2 diabetes. Second, our study's cross-sectional design means that causality cannot be inferred from this study alone. However, prospective investigations show that anthropometric measures are powerful predictors of type 2 diabetes [19]. Third, we did not adjust our associations for some health behaviours (e.g. diet), which may result in some confounding. Fourth, we used self-report to assign ethnicity, which may result in some misclassification. However, in a separate analysis where we genotyped EpiDREAM participants using a custom-made 50K single nucleotide polymorphism chip for variation in genes related to cardiometabolic risk [36], we found that self-reported ethnicity was strongly correlated with genotype cluster and hence ancestral origin determined by multidimensional scaling [37]. Fifth, we were not able to explore the biological basis of associations and interactions observed in this study.

Conclusions

The combinations of BMI and WHR, or of waist circumference and hip circumference have the best explanatory power for type 2 diabetes and glucose status compared with a single anthropometric measure. Measurement of both waist circumference and hip circumference is required to optimally identify people with elevated glucose levels.

Acknowledgements This analysis was supported by a Frederick Banting and Charles Best Canada Graduate Scholarship Doctoral Research Award from the Canadian Institutes of Health Research to L. de Koning. EpiDREAM was supported by grants from the Heart and Stroke Foundation of Canada, the Canadian Institutes of Health Research, Sanofi-Aventis, GlaxoSmithKline and King Pharmaceuticals. We thank L. Dyal (Population Health Research Institute, Hamilton, ON, Canada) for statistical advice and database support. H. C. Gerstein holds the Population Health Research Institute Chair in Diabetes Research. S. S. Anand holds the Michael G. De Groote Heart and Stroke Foundation of Ontario Chair in Population Health Research and the Eli Lilly May Cohen Chair in Women's Health. S. Yusuf holds a Heart and Stroke Foundation of Ontario Chair in Cardiovascular Research.

Duality of interest The authors declare that there is no duality of interest associated with this manuscript.

References

1. World Health Organization (2006) Obesity and Overweight. Available from www.who.int/mediacentre/factsheets/fs311/en/index.html, accessed 17 February 2010.
2. Kelly T, Yang W, Chen CS, Reynolds K, He J (2008) Global burden of obesity in 2005 and projections to 2030. Int J Obes (Lond) 32:1431–1437
3. The World Bank (2010) Population Projections—HNPStats: 2005–2050 Total Population. Available from http://siteresources.worldbank.org/EXTHNPSTATS/Resources/Popprojectiontotal.xls, accessed 17 February 2010
4. International Diabetes Federation (2006) Diabetes Atlas. International Diabetes Federation, Brussels
5. Wild S, Roglic G, Green A, Sicree R, King H (2004) Global prevalence of diabetes: estimates for the year 2000 and projections for 2030. Diabetes Care 27:1047–1053
6. Shai I, Jiang R, Manson JE et al (2006) Ethnicity, obesity, and risk of type 2 diabetes in women: a 20-year follow-up study. Diabetes Care 29:1585–1590
7. Yusuf S, Hawken S, Ounpuu S et al (2005) Obesity and the risk of myocardial infarction in 27,000 participants from 52 countries: a case–control study. Lancet 366:1640–1649
8. Pouliot MC, Despres JP, Nadeau A et al (1992) Visceral obesity in men. Associations with glucose tolerance, plasma insulin, and lipoprotein levels. Diabetes 41:826–834
9. Meisinger C, Doring A, Thorand B, Heier M, Lowel H (2006) Body fat distribution and risk of type 2 diabetes in the general population: are there differences between men and women? The MONICA/KORA Augsburg cohort study. Am J Clin Nutr 84:483–489
10. Li C, Engstrom G, Hedblad B, Calling S, Berglund G, Janzon L (2006) Sex differences in the relationships between BMI, WHR and incidence of cardiovascular disease: a population-based cohort study. Int J Obes (Lond) 30:1775–1781
11. Karter AJ, Mayer-Davis EJ, Selby JV et al (1996) Insulin sensitivity and abdominal obesity in African-American, Hispanic, and non-Hispanic white men and women. The Insulin Resistance and Atherosclerosis Study. Diabetes 45:1547–1555
12. Harris MM, Stevens J, Thomas N, Schreiner P, Folsom AR (2000) Associations of fat distribution and obesity with hypertension in a bi-ethnic population: the ARIC study. Atherosclerosis Risk in Communities Study. Obes Res 8:516–524

13. Gerstein HC, Yusuf S, Holman R, Bosch J, Pogue J (2004) Rationale, design and recruitment characteristics of a large, simple international trial of diabetes prevention: the DREAM trial. Diabetologia 47:1519–1527
14. World Health Organization (2006) Definition and diagnosis of diabetes mellitus and intermediate hyperglycemia. Report of a WHO/IDF Consultation. Available from www.idf.org/webdata/docs/WHO_IDF_definition_diagnosis_of_diabetes.pdf, accessed 17 February 2010.
15. The SAS corporation (2009) Sample 25017: nonparametric comparison of areas under correlated ROC curves. Available from http://support.sas.com/kb/25/017.html, accessed 17 February 2010.
16. Higgins JP, Thompson SG, Deeks JJ, Altman DG (2003) Measuring inconsistency in meta-analyses. BMJ 327:557–560
17. Vazquez G, Duval S, Jacobs DR Jr, Silventoinen K (2007) Comparison of body mass index, waist circumference, and waist/hip ratio in predicting incident diabetes: a meta-analysis. Epidemiol Rev 29:115–128
18. Qiao Q, Nyamdorj R (2010) Is the association of type II diabetes with waist circumference or waist-to-hip ratio stronger than that with body mass index? Eur J Clin Nutr 64:30–34
19. Wang Y, Rimm EB, Stampfer MJ, Willett WC, Hu FB (2005) Comparison of abdominal adiposity and overall obesity in predicting risk of type 2 diabetes among men. Am J Clin Nutr 81:555–563
20. Snijder MB, Dekker JM, Visser M et al (2004) Trunk fat and leg fat have independent and opposite associations with fasting and postload glucose levels: the Hoorn study. Diabetes Care 27:372–377
21. Snijder MB, Zimmet PZ, Visser M, Dekker JM, Seidell JC, Shaw JE (2004) Independent and opposite associations of waist and hip circumferences with diabetes, hypertension and dyslipidemia: the AusDiab Study. Int J Obes Relat Metab Disord 28:402–409
22. Lissner L, Bjorkelund C, Heitmann BL, Seidell JC, Bengtsson C (2001) Larger hip circumference independently predicts health and longevity in a Swedish female cohort. Obes Res 9:644–646
23. Seidell JC, Perusse L, Despres JP, Bouchard C (2001) Waist and hip circumferences have independent and opposite effects on cardiovascular disease risk factors: the Quebec Family Study. Am J Clin Nutr 74:315–321
24. Canoy D, Boekholdt SM, Wareham N et al (2007) Body fat distribution and risk of coronary heart disease in men and women in the European Prospective Investigation Into Cancer and Nutrition in Norfolk cohort: a population-based prospective study. Circulation 116:2933–2943
25. Allison DB, Paultre F, Goran MI, Poehlman ET, Heymsfield SB (1995) Statistical considerations regarding the use of ratios to adjust data. Int J Obes Relat Metab Disord 19:644–652
26. Kamel EG, McNeill G, Han TS et al (1999) Measurement of abdominal fat by magnetic resonance imaging, dual-energy X-ray absorptiometry and anthropometry in non-obese men and women. Int J Obes Relat Metab Disord 23:686–692
27. Fox CS, Massaro JM, Hoffmann U et al (2007) Abdominal visceral and subcutaneous adipose tissue compartments: association with metabolic risk factors in the Framingham Heart Study. Circulation 116:39–48
28. Margolis KL, Bonds DE, Rodabough RJ et al (2004) Effect of oestrogen plus progestin on the incidence of diabetes in postmenopausal women: results from the Women's Health Initiative Hormone Trial. Diabetologia 47:1175–1187
29. Bonds DE, Lasser N, Qi L et al (2006) The effect of conjugated equine oestrogen on diabetes incidence: the Women's Health Initiative randomised trial. Diabetologia 49:459–468
30. Katzmarzyk PT, Malina RM (1998) Obesity and relative subcutaneous fat distribution among Canadians of First Nation and European ancestry. Int J Obes Relat Metab Disord 22:1127–1131
31. Piers LS, Rowley KG, Soares MJ, O'Dea K (2003) Relation of adiposity and body fat distribution to body mass index in Australians of Aboriginal and European ancestry. Eur J Clin Nutr 57:956–963
32. Aloia JF, Vaswani A, Mikhail M, Flaster ER (1999) Body composition by dual-energy X-ray absorptiometry in black compared with white women. Osteoporos Int 10:114–119
33. Rush EC, Goedecke JH, Jennings C et al (2007) BMI, fat and muscle differences in urban women of five ethnicities from two countries. Int J Obes (Lond) 31:1232–1239
34. Lear SA, Humphries KH, Kohli S, Chockalingam A, Frohlich JJ, Birmingham CL (2007) Visceral adipose tissue accumulation differs according to ethnic background: results of the Multicultural Community Health Assessment Trial (M-CHAT). Am J Clin Nutr 86:353–359
35. Lear SA, Humphries KH, Kohli S, Birmingham CL (2007) The use of BMI and waist circumference as surrogates of body fat differs by ethnicity. Obesity (SilverSpring) 15:2817–2824
36. Keating BJ, Tischfield S, Murray SS et al (2008) Concept, design and implementation of a cardiovascular gene-centric 50 k SNP array for large-scale genomic association studies. PLoS ONE 3:e3583
37. Bailey SD, Xie C, Do R, et al. (2009) Genetic variation at the NFATC2 locus iIncreases edema in the Diabetes REduction Assessment with Ramipril and Rosiglitazone Medication (DREAM) Study. The American Society of Human Genetics 59th Annual Meeting, Honolulu, HI, abstract no. 306