Comparison of Body Mass Index, Waist Circumference, and Waist/Hip Ratio in Predicting Incident Diabetes: A Meta-Analysis

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Body mass index, waist circumference, and waist/hip ratio have been shown to be associated with type 2 diabetes. From the clinical perspective, central obesity (approximated by waist circumference or waist/hip ratio) is known to generate diabetogenic substances and should therefore be more informative than general obesity (body mass index). Because of their high correlation, from the statistical perspective, body mass index and waist circumference are unlikely to yield different answers. To compare associations of diabetes incidence with general and central obesity indicators, the authors conducted a meta-analysis based on published studies from 1966 to 2004 retrieved from a PubMed search. The analysis was performed with 32 studies out of 432 publications initially identified. Measures of association were transformed to log relative risks per standard deviation (pooled across all studies) increase in the obesity indicator and pooled using random effects models. The pooled relative risks for incident diabetes were 1.87 (95% confidence interval (CI): 1.67, 2.10), 1.87 (95% CI: 1.58, 2.20), and 1.88 (95% CI: 1.61, 2.19) per standard deviation of body mass index, waist circumference, and waist/hip ratio, respectively, demonstrating that these three obesity indicators have similar associations with incident diabetes. Although the clinical perspective focusing on central obesity is appealing, further research is needed to determine the usefulness of waist circumference or waist/hip ratio over body mass index.

body fat distribution; body mass index; diabetes mellitus, type 2; meta-analysis; obesity; waist-hip ratio

INTRODUCTION

Obesity has become a major worldwide epidemic affecting more than 300 million people. It is an important risk factor for diabetes mellitus, type 2, a chronic disorder of carbohydrate, fat, and protein metabolism. From the clinical perspective, visceral adipose tissue is known to generate diabetogenic substances (1) and, as such, may be more informative than total fat for diagnostic evaluation. The standard epidemiologic translation of these important clinical facts uses anthropometric measures. Waist circumference and waist/hip ratio have been used as measures of central obesity (where visceral adipose tissue is stored), and body mass index (kg/m²) has been used as a measure of general obesity (2).

Clinical evidence suggests that the association of diabetes with central obesity is stronger than the association with general fat. Studies using computed tomography and magnetic resonance imaging have provided further evidence to support that central obesity, visceral adipose tissue, and upper-body nonvisceral fat are the major contributors to the metabolic complications (3–6). Central obesity has been associated with decreased glucose tolerance, alterations in glucose insulin homeostasis, reduced metabolic clearance of insulin, and decreased insulin-stimulated glucose disposal.

In addition, studies that have analyzed the association of anthropometric measures and abdominal visceral fat have found waist circumference to be a better measure of central obesity because it is a better predictor of abdominal visceral fat obtained with computed tomography than is waist/hip
ratio, and it can be easily measured and interpreted (2, 7–10). However, waist circumference cannot distinguish ab-
dominal subcutaneous fat, total abdominal fat, and total
body fat, and it is strongly correlated with body mass index.
Body mass index has been shown to be a good indicator of
general fatness (fat areas in the arm, thigh, and waist using
computed tomography scans), muscularity (muscle area in
the thigh), and frame size (bone area in thighs) (11).

As expected, epidemiologic studies have demonstrated
that these three obesity indicators are strong and consistent
predictors of diabetes mellitus, type 2. However, despite the
clear, clinical difference between visceral and other forms of
fat, little epidemiologic difference would be expected in the
relations of diabetes with body mass index versus waist
circumference. From a statistical perspective, the two meas-
ures yield similar information, with the correlation coeffi-
cient typically about 0.8 (12). Several studies have shown
that waist circumference is a better predictor of diabetes
mellitus, type 2, than is body mass index, but these findings
are inconclusive (13–15), while other studies provide evi-
dence that waist/hip ratio has a positive effect independent
of body mass index (16–18). In addition, the ability of these
obesity indicators to predict diabetes may differ by ethnicity,
age, and sex (19–22). For example, among Asian popula-
tions, central obesity has been shown to be a more consistent
predictor of diabetes than is total obesity (18, 23), while
general obesity has been shown to be a better predictor
among White US populations and Europeans (24, 25).

To study the magnitude of the association among differ-
et obesity indicators in multiethnic populations comprising
studies worldwide, we performed a meta-analysis of pub-
lished studies that reported the association between obesity
and incident diabetes. Additionally, we explored if the asso-
ciations differed by region and other population character-
istics. Finally, we investigated if the study designs and
model assumptions contributed to the heterogeneity of the
reported results.

**RESEARCH DESIGN AND METHODS**

**Data sources**


**FIGURE 1.** Study selection diagram for the meta-analysis of studies published from 1966 to 2004. NIDDM, non-insulin-dependent diabetes mellitus; WC, waist circumference; WHR, waist/hip ratio.
was performed during April 2002 (search 1) and updated in December 2004 (search 2) to select relevant publications. Refer to figure 1 for selection criteria.

Study selection

The search was limited to articles published in English. Study selection was performed with two levels of study screening. At the first level, abstracts were examined by two independent reviewers, using the following criteria: diabetes as the outcome, at least one indicator of abdominal obesity as the exposure or as a confounding factor, and follow-up study. Full manuscripts were then obtained for all publications accepted at level 1 screening. For level 2 screening, we verified that relevant data were available and that multiple publications describing the same study population were entered only once in the meta-analysis. When a study had multiple publications, the latest reference in which relevant data were available was used.

Data extraction

From each study, we retrieved study population characteristics (age range, gender, geographic area, ethnicity, inclusion criteria, incident diabetes rate, and mean and variability measure for each obesity indicator reported); study design characteristics (sampling design, follow-up time, number of visits, and sample size); diabetes assessment (epidemiologic criteria and collection instrument); and model assumptions (obesity indicator representation, parameter of association, level of covariate adjustment, and subgroup analysis). Estimates of magnitude of association and variability, that is, standard errors or 95 percent confidence intervals, were extracted over the entire study samples or by subgroups. Several publications reported associations with different levels of covariate adjustment, all of which were extracted.

Statistical analysis

The publications retrieved used different representations of the association of diabetes with the obesity indicator (continuous, categorical, and baseline means for diabetes cases and noncases). The measures were transformed to calculate a log-linear slope with diabetes risk per 1-standard deviation (pooled across all studies) increase of the obesity indicator. To transform measures based on categorical representations, the obesity indicators were assumed to be normally distributed, and all values in a category were assigned to the median value. This assumption was checked by repeating the analysis using a gamma distribution, revealing no differences in the individual study associations to the second decimal place. For studies with three or more categories of the obesity indicator, the slope was estimated with the method of Greenland and Longnecker (26) using STATA’s gllt function; StataCorp LP, College Station, Texas), which calculates a weighted linear regression of the natural logarithm (log) of the relative risks across anthropometric categories, taking into account the correlation between estimates. For binary representation of the obesity indicator, classified according to the median value, the log relative risks were divided by the interquartile range. For studies with three or more categories reporting the association of only two categories, the log relative risks were divided by the distance between the median values of the reported categories. For studies with only baseline means and standard errors, the log relative risks were calculated from a simulation of cases and noncases assuming a normal distribution. Where the study measures of association were stratified by subgroups, stratum-specific estimates were pooled using a fixed-effects model, weighted by the inverse subgroup variance.

Studies were classified by region for comparative analysis. Degree of obesity and diabetes incidence were compared across populations. Region-specific means and standard deviations were pooled from individual studies to describe the degree of obesity measured by body mass index, waist circumference, and waist/hip ratio. Region-specific incident diabetes rates were calculated as geometric means.

To assess the association between the three measures of obesity and incident diabetes, we calculated pooled estimates across all studies for the relative risk using a random-effects model. Relative risks (RRs) were expressed per standard deviation (computed across all studies) of each indicator (body mass index (BMI), waist circumference (WC), waist/hip ratio (WHR)). The difference between RR_BMI and RR_WC (or RR_BMI and RR_WHR) was evaluated only in studies that included both of each pair of indicators. The analysis was performed using RR_BMI and RR_WC as repeated dependent variables within each study in SAS, version 9.1.3, PROC MIXED (27), following the method of van Houwelingen et al. (28). Within-study variances of the relative risks were fixed for each study using the PARMS (or parameter) statement, which declares the parameters and specifies their initial values. A similar analysis was done for RR_BMI and RR_WHR.

$F^2$ was used to describe the proportion of total variation among study-specific estimates that is due to heterogeneity (29). Heterogeneity was investigated ecologically by comparing pooled relative risks of subgroups defined by region, gender, mean body mass index, mean age, incident diabetes rate, and criteria used to define the target sample. Tests for differences between subgroups were performed unadjusted for other study level characteristics using meta-regression. Further exploration of the heterogeneity of the relative risk due to design characteristics and model assumptions was performed only for body mass index, including body mass index representation, reported parameter of association, outcome assessment, level of covariate adjustment, and follow-up time.

Additionally, funnel plots with pseudo 95 percent confidence intervals were used for visual assessment of publication bias, and the trim and fill method (30) was used to estimate any possible publication bias. All meta-analyses except the bivariate analyses were performed using the STATA, version 8.2, statistical package (31).

RESULTS

Figure 1 presents a flow diagram outlining the systematic review process. An initial search generated a list of 432 publications (290 in April 2002 and 142 in December 2004). After review of the abstracts, 47 publications...
(36 from search 1 and 11 from search 2) met inclusion criteria. From those 47 publications, we included data from 29 publications, reporting on 32 distinct study populations (13, 16–18, 24, 32–56). Burke et al. (47) included a subset of Mexican origin subjects from the San Antonio Heart Study (13) to compare them with those from the Mexico City Diabetes Study. Although this study contained a subset of subjects already in our study sample, the study was retained because the majority of the sample targeted a different population. In addition, Edelstein et al. (56) reported the result of six studies, four not previously included. Only studies concerned with body mass index, waist circumference, and waist/hip ratio were included in the present analysis. Other anthropometric indicators reported in the publications were the subscapular/triceps skinfold thickness ratio, waist/thigh ratio, subscapular skinfold thickness, triceps skinfold thickness, skinfold thickness sum, hip circumference, and waist/height ratio.

Table 1 provides a summary of the characteristics of the included studies, and Table 2 provides a detailed description of each study in the meta-analysis. Among the studies included, four targeted men, three targeted women, and 25 targeted both genders; the age range was 20–80 years. All studies analyzed the progression from nondiabetes to diabetes. However, several targeted more restricted populations; for example, the Mauritius study (40) targeted subjects with normal glucose tolerance, five studies targeted subjects with impaired glucose tolerance, and four studies included only participants free of chronic conditions. The studies were classified in three regions based on geographic proximity: Europe (nine studies), United States (12 studies), and Asia (four studies). Seven studies (36, 40, 44, 45, 47, 48, 55) were excluded from regional comparisons because they differed from the core population of each region or were located in other geographic areas. The study designs differed in sampling design, follow-up time, number of follow-up visits, and sample size. Diabetes assessment relied on different instruments and diagnostic criteria (57–60). In terms of the analysis, differences relied on the representation of the obesity–diabetes association, statistical approach, level of adjustment, and level of stratification.

Table 3 provides descriptive information for body mass index (kg/m²), waist circumference (cm), and waist/hip ratio by region. Information reported in publications was sometimes unadjusted and sometimes adjusted for age, sex, or other factors, and in two studies not reported. Pooled means for body mass index, waist circumference, and waist/hip ratio were 25.8 (standard deviation: 4.3), 87.2 (SD: 11.6), and 0.84 (SD: 0.07), respectively. People from Asian studies were identified as being the leanest: 24.2 (SD: 3.1) kg/m² and 79.7 (SD: 8.6) cm for body mass index and waist circumference, respectively, while studies from Europe and the United States reported significantly higher values: 26.3 (SD: 3.4) kg/m² and 92.1 (SD: 9.9) cm for European studies and 26.6 (SD: 4.5) kg/m² and 88.2 (SD: 10.9) cm for studies in the United States. Body mass index and waist circumference, but not waist/hip ratio, reflected regional differences in degree of obesity between individuals from different regions (p values for geographic differences were 0.02 for both body mass index and waist circumference, using an F test for overall difference). Correlations between obesity indicators at the study level were similar for those observed at the

### TABLE 1. Summary of characteristics of studies between 1985 and 2004 included in the meta-analysis that reported the association of body mass index, waist circumference, or waist/hip ratio and incident diabetes

<table>
<thead>
<tr>
<th>Concept</th>
<th>Characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Population characteristics</strong></td>
<td></td>
</tr>
<tr>
<td>Sex</td>
<td>Men (n = 4); women (n = 3); both (n = 25)</td>
</tr>
<tr>
<td>Age range</td>
<td>20–80 years</td>
</tr>
<tr>
<td>Geographic regions</td>
<td>United States (n = 12); Europe (n = 9); Asia (n = 4); others (n = 7)</td>
</tr>
<tr>
<td>Baseline glycemic status</td>
<td>Nondiabetic (n = 22); nondiabetic and free of chronic conditions (n = 4); normoglycemic (n = 1); impaired glucose tolerance (n = 5)</td>
</tr>
<tr>
<td><strong>Design characteristics</strong></td>
<td></td>
</tr>
<tr>
<td>Sampling design</td>
<td>Cohort (n = 31); nested-case control (n = 1)</td>
</tr>
<tr>
<td>Follow-up time</td>
<td>2–25 years</td>
</tr>
<tr>
<td>No. of visits</td>
<td>1–15 visits</td>
</tr>
<tr>
<td>Sample size</td>
<td>72–31,702 subjects</td>
</tr>
<tr>
<td>Assessment of event</td>
<td>Self-report only (n = 2); medical records only (n = 2); clinical measurement together with self-report and use of hypoglycemic medications (n = 28)</td>
</tr>
<tr>
<td>Epidemiologic criteria</td>
<td>WHO 85* (n = 15); WHO 99* (n = 6); ADA 97* (n = 4); 2-hour oral glucose tolerance test (n = 1); self-reported according to current clinical criteria (n = 6)</td>
</tr>
<tr>
<td><strong>Obesity indicators</strong></td>
<td></td>
</tr>
<tr>
<td>Variable</td>
<td>Body mass index (n = 32); waist circumference (n = 18); waist/hip ratio (n = 25)</td>
</tr>
<tr>
<td>Exposure representation</td>
<td>Linear (n = 15); multiple categories (n = 6); binary (n = 5); baseline means (n = 6)</td>
</tr>
<tr>
<td>Association parameter</td>
<td>Odds ratio (n = 21); rate ratio (n = 11)</td>
</tr>
<tr>
<td>Level of covariate adjustment</td>
<td>Crude (n = 14); age and sex (n = 14); further adjustment using other risk factors (n = 1); adjustment that included body shape or total obesity (n = 3). Note: three studies presented more than one level of adjustment.</td>
</tr>
<tr>
<td>Stratified</td>
<td>Overall (n = 25): reported by sex, age group, or ethnic group (n = 7)</td>
</tr>
</tbody>
</table>

* WHO 85, World Health Organization 1985 criteria (fasting plasma glucose: ≥7.8 mmol/liter (140 mg/day/liter) or 2-hour postplasma glucose: ≥11.1 mmol/liter (200 mg/day/liter)); WHO 99, World Health Organization 1999 criteria (fasting plasma glucose: ≥7 mmol/liter (126 mg/day/liter) or 2-hour post-plasma glucose: ≥11.1 mmol/liter (200 mg/day/liter)); ADA 97, American Diabetes Association 1997 criteria (fasting plasma glucose: ≥7 mmol/liter (126 mg/day/liter)).
Meta-Analysis of Obesity and Diabetes

... individual level (13, 33): 0.88, 0.34, and 0.44 for body mass index–waist circumference, body mass index–waist/hip ratio, and waist circumference–waist/hip ratio, respectively.

Incident diabetes rates were highest for people from US studies (13.5 new cases per 1,000 person-years) and lowest for people from Asian studies (5.2 new cases per 1,000 person-years). They appear to vary according to differences in inclusion criteria and other individual characteristics of the study populations, including the level of obesity. However, diabetes rates should be interpreted with caution because they were reported at various levels of adjustment.

Figures 2, 3, and 4 present the pooled and study-level relative risk for each of the obesity indicators. The pooled estimates of RR_BMI (n = 32) (SD: 4.3) were 1.92 (95 percent confidence interval (CI): 1.70, 2.17). Among the 18 studies that included both body mass index and waist circumference, RR_BMI was 1.72 (95 percent CI: 1.47, 2.02), and RR_WC (SD: 11.6) was 1.87 (95 percent CI: 1.62, 2.15). In the 25 studies that included both body mass index and waist/hip ratio, RR_BMI was 1.98 (95 percent CI: 1.70, 2.30) and RR_WHR (SD: 0.84) was 1.82 (95 percent CI: 1.55, 2.13). Neither comparison, body mass index and waist circumference (p = 0.50) or body mass index and waist/hip ratio (p = 0.73), revealed a significant difference in the magnitude of association. Heterogeneity was present for all obesity indicators: I² > 0.90.

Figures 5, 6, and 7 present the pooled RR_BMI, RR_WC, and RR_WHR stratified by study-level characteristics. Differences in the obesity–diabetes relative risks were marked between groups defined by study incident diabetes rate and inclusion criteria for all three obesity indicators. Those studies that targeted a sample of subjects with a higher diabetes rate or with impaired glucose tolerance presented a shallower obesity–diabetes relative risk. When pooled relative risks between obesity indicators were compared, some modest differences were found by region and age. RR_BMI and RR_WC were similar for the three regions but were shallower for RR_WHR-Asia (1.4 (95 percent CI: 1.1, 1.7)) compared with RR_WHR-Europe (1.9 (95 percent CI: 1.7, 2.2)) and RR_WHR-United States (1.7 (95 percent CI: 1.4, 2.2)). In addition, in studies where the mean age was less than 50 years, RR_WHR (2.1 (95 percent CI: 1.7, 2.6)) was higher than RR_BMI (1.7 (95 percent CI: 1.4, 2.0)) and RR_WC (1.6 (95 percent CI: 1.4, 1.9)). For studies where the mean age was greater than or equal to 50 years, RR_WHR (1.7 (95 percent CI: 1.5, 2.0)) was weaker than RR_BMI (2.0 (95 percent CI: 1.7, 2.3)) and RR_WC (2.0 (95 percent CI: 1.6, 2.7)).

Figure 8 presents the pooled RR_BMI estimates by study design and model characteristic groups. Differences in study design, outcome assessment, and model assumption may explain some of the heterogeneity of the relative risks across studies. However, none of the characteristics alone seems to play an important role in the level of heterogeneity. In addition, it is not possible to differentiate the impact of each component with a multivariable approach because of the scarcity of studies in each category. Analysis was repeated for RR_WC and RR_WHR, and results were consistent with those found with RR_BMI.

The funnel plots and trim and fill method showed no publication bias for RR_BMI and RR_WC (figures not shown).

DISCUSSION

The association of body mass index, waist circumference, and waist/hip ratio with incident diabetes was confirmed in our study by the significant pooled estimates of the relative risk. When comparing the associations in the subset of studies with both body mass index and waist circumference, the pooled RR_WC was modestly stronger than the RR_BMI. When comparing the RR_BMI and RR_WHR, RR_BMI was modestly stronger. None of these differences was statistically significant.

A recent meta-analysis of the association of body mass index and incident diabetes found similar results (61), although this study differed in some analytical aspects in estimating study-level relative risk, study selection, and target population. Because our meta-analysis focused on studies reporting an additional measure of central obesity, we have fewer studies included in our analyses.

Ford et al. (12) support the use of waist circumference as a measure of obesity to predict health risk. Among their arguments are that waist circumference has been shown to be a good or better predictor than body mass index of the metabolic syndrome, diabetes, cardiovascular disease, and all-cause mortality; it provides information about health risk in addition to body mass index; and it is conceptually easy to measure, although it does require some training and standardization. However, others have noted that substitution of body mass index by waist circumference as an indicator of risk for cardiovascular disease and diabetes may be an oversimplification (2, 11, 62). Some counterarguments are that waist circumference is strongly correlated to body mass index (r = 0.8) (12, 13, 33, 63); waist circumference does not differentiate between subcutaneous fat and visceral fat; it has not been shown that a consistent association exists between waist circumference with visceral fat after adjustment for age and body mass index; and body fat distribution is different across racial, sex, and age (2, 10, 62, 64, 65) strata.

Other indicators have been suggested to describe fat distribution associated with abdominal obesity (2). For example, the subscapular/triceps skinfold ratio has been used to describe central versus peripheral obesity. The waist/hip ratio and the waist/thigh ratio have been used to identify upper versus lower body obesity. In addition, other indices, such as waist/height ratio, conicity index, and abdominal to mid-thigh girth, have been developed on the basis of a variety of criteria. However, ratios are more difficult to interpret biologically, are less sensitive to weight gain, and have statistical limitations (66). Because relatively few studies have considered these indicators, we did not include them in our meta-analysis.

In our analysis, we included waist/hip ratio because it was the most common obesity-related predictor of diabetes after body mass index and it has a weaker correlation with body mass index (r = 0.4) (13, 33) than other waist circumference.
TABLE 2. Description of characteristics of studies between 1985 and 2004 included in the meta-analysis that reported the association of body mass index, waist circumference, or waist/hip ratio and incident diabetes

<table>
<thead>
<tr>
<th>First author (reference no.)</th>
<th>Study name, location (acronym)</th>
<th>Baseline years</th>
<th>Mean years of follow-up or range</th>
<th>Follow-up (no.)</th>
<th>Population selection</th>
<th>Sample size (no.)</th>
<th>Mean age or range (years)</th>
<th>Men (%)</th>
<th>Diabetes rate/1,000 person-years</th>
<th>Anthropometric role</th>
<th>Assessment of event</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feskens (32)</td>
<td>Zutphen Study, Netherlands (Zutphen)</td>
<td>1960</td>
<td>25</td>
<td>15 visits</td>
<td>NDM*</td>
<td>841</td>
<td>40–59</td>
<td>100</td>
<td>3.8</td>
<td>Risk factor</td>
<td>Self-reported physician diagnosed or use of medications</td>
</tr>
<tr>
<td>Cassano (18)</td>
<td>Normative Aging Study, United States (NAS)</td>
<td>1963–1970</td>
<td>18</td>
<td>4 visits</td>
<td>NCHD* and NC*</td>
<td>1,972</td>
<td>20–80</td>
<td>100</td>
<td>6.4</td>
<td>Exposure</td>
<td>Clinical diagnosis with WHO 85* in study examination or diagnosed by a physician involved in the study</td>
</tr>
<tr>
<td>Ohlson (33)</td>
<td>Prospective Population Study of Men, Gothenburg, Sweden (Goteborg men)</td>
<td>1963</td>
<td>14</td>
<td>1 visit</td>
<td>NDM</td>
<td>766</td>
<td>50</td>
<td>100</td>
<td>4.5</td>
<td>Risk factor</td>
<td>Self-reported physician diagnosed, clinical diagnosis with WHO 85, or hospital and death register</td>
</tr>
<tr>
<td>Lundgren (17)</td>
<td>Prospective Population Study of Women, Gothenburg, Sweden (Goteborg women)</td>
<td>1968–1981</td>
<td>12</td>
<td>2 visits</td>
<td>NDM</td>
<td>1,318</td>
<td>38–60</td>
<td>0</td>
<td>2.5</td>
<td>Confounder</td>
<td>Self-reported physician diagnosed or clinical diagnosis with WHO 80*</td>
</tr>
<tr>
<td>Lipton (34)</td>
<td>First National Health and Nutrition Examination Survey, United States (NHANES I)</td>
<td>1971–1981</td>
<td>16</td>
<td>Registry</td>
<td>NDM</td>
<td>11,097</td>
<td>25–70</td>
<td>40</td>
<td>5.0</td>
<td>Risk factor</td>
<td>Self-reported physician diagnosed, hospital, nursing, or death register</td>
</tr>
<tr>
<td>Wei (13)</td>
<td>San Antonio Heart Study, United States (SAHS)</td>
<td>1971–1987</td>
<td>7.2</td>
<td>1 visit</td>
<td>NDM</td>
<td>721</td>
<td>25–64</td>
<td>37</td>
<td>20.2</td>
<td>Exposure</td>
<td>Clinical diagnosis with WHO 80, or self-reported physician diagnosed and use of medication</td>
</tr>
<tr>
<td>Folsom (35)</td>
<td>Iowa Women’s Health Study, United States (IOWA)</td>
<td>1986</td>
<td>11–12</td>
<td>4 surveys</td>
<td>NDM, NCHD, and NC</td>
<td>31,702</td>
<td>55–69</td>
<td>0</td>
<td>4.3</td>
<td>Exposure</td>
<td>Self-reported physician diagnosed</td>
</tr>
<tr>
<td>Young (36)</td>
<td>Northern Native Canadian Cohort Study, Canada (N-NCCS)</td>
<td>1986</td>
<td>4–5</td>
<td>Registry</td>
<td>NDM</td>
<td>630</td>
<td>20–64</td>
<td>44</td>
<td>8.0</td>
<td>Risk factor</td>
<td>Medical records with diagnosis consistent with WHO 85</td>
</tr>
<tr>
<td>Mykkänen (37)</td>
<td>Finland study, Finland (FINRISK)</td>
<td>1986–1988</td>
<td>3.5</td>
<td>1 visit</td>
<td>NDM</td>
<td>892</td>
<td>65–74</td>
<td>36</td>
<td>22.1</td>
<td>Risk factor</td>
<td>Clinical diagnosis with WHO 85 criteria in study examination</td>
</tr>
<tr>
<td>Chan (24)</td>
<td>Male Health Professionals Study, United States (MHPSS)</td>
<td>1986–1992</td>
<td>5</td>
<td>3 surveys</td>
<td>NDM, NCHD, and NC</td>
<td>27,983</td>
<td>40–75</td>
<td>100</td>
<td>1.9</td>
<td>Exposure</td>
<td>Self-report of any symptoms, clinical diagnosis with WHO 85 on two occasions, or medication validation</td>
</tr>
<tr>
<td>Carey (38)</td>
<td>Nurses’ Health Study, United States (NHS)</td>
<td>1986–1992</td>
<td>7–8</td>
<td>4 surveys</td>
<td>NDM</td>
<td>43,581</td>
<td>30–55</td>
<td>0</td>
<td>2.2</td>
<td>Exposure</td>
<td>Self-reported physician diagnosed or use of medication, or clinical diagnosis with WHO 99*</td>
</tr>
<tr>
<td>Schmidt (39)</td>
<td>Atherosclerosis Risk in Communities Study, United States (ARIC)</td>
<td>1987</td>
<td>7</td>
<td>3 visits</td>
<td>NDM</td>
<td>11,880</td>
<td>45–64</td>
<td>46</td>
<td>16.1</td>
<td>Confounder</td>
<td>Self-reported physician diagnosed or use of medication, or clinical diagnosis with WHO 99</td>
</tr>
<tr>
<td>Boyko (40)</td>
<td>Mauritius Noncommunicable Disease Study, Mauritius (Mauritius)</td>
<td>1987–1992</td>
<td>5</td>
<td>1 visit</td>
<td>NGT*</td>
<td>2,605</td>
<td>25–74</td>
<td>49</td>
<td>12.2</td>
<td>Risk factor</td>
<td>Self-reported physician diagnosed or use of medications, or clinical diagnosis with WHO 99</td>
</tr>
<tr>
<td>Snijder (41)</td>
<td>Hoorn Study, Netherlands (Hoorn)</td>
<td>1989–1996</td>
<td>6.4</td>
<td>1 visit</td>
<td>NDM</td>
<td>1,357</td>
<td>50–75</td>
<td>46</td>
<td>15.2</td>
<td>Exposure</td>
<td>Self-reported physician diagnosed or use of medication, or clinical diagnosis with WHO 99</td>
</tr>
<tr>
<td>Festa (42)</td>
<td>Insulin Resistance Atherosclerosis Study, United States (IRAS)</td>
<td>1992–1994</td>
<td>5.2</td>
<td>2 visits</td>
<td>NDM</td>
<td>1,047</td>
<td>55</td>
<td>32</td>
<td>26.4</td>
<td>Confounder</td>
<td>Clinical diagnosis with WHO 85</td>
</tr>
<tr>
<td>Shin (43)</td>
<td>Yonchon County Study, Korea (Yonchon)</td>
<td>1993–1995</td>
<td>2</td>
<td>1 visit</td>
<td>NDM</td>
<td>1,193</td>
<td>30</td>
<td>43</td>
<td>Risk factor</td>
<td>Clinical diagnosis with WHO 85</td>
<td></td>
</tr>
<tr>
<td>Sargeant (44)</td>
<td>Jamaica Study, Jamaica (Jamaica)</td>
<td>1993–1996</td>
<td>4</td>
<td>1 visit</td>
<td>NDM</td>
<td>728</td>
<td>25–74</td>
<td>40</td>
<td>1.84</td>
<td>Exposure</td>
<td>Self-reported physician diagnosed or use of medications, or clinical diagnosis with WHO 99</td>
</tr>
<tr>
<td>Author</td>
<td>Study Details</td>
<td>Year</td>
<td>Visit Type</td>
<td>NDM</td>
<td>Age Range</td>
<td>Sex</td>
<td>Risk Factor</td>
<td>Exposure Details</td>
<td></td>
<td></td>
<td></td>
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<tr>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>McNeely (45)</td>
<td>Japanese-American Community Diabetes Study, United States (JACDS)</td>
<td>1983-1988</td>
<td>5</td>
<td>1 visit</td>
<td>NDM</td>
<td>466</td>
<td>34-75</td>
<td>52</td>
<td>21.0</td>
<td>Exposure Clinical diagnosis with WHO 99 or use of medications</td>
<td></td>
</tr>
<tr>
<td>Wang (46)</td>
<td>Cardiovascular Disease Risk Factor Two-Township Study, Taiwan (Taiwan)</td>
<td>1990-1993</td>
<td>5</td>
<td>1 visit</td>
<td>NDM</td>
<td>2,190</td>
<td>35-74</td>
<td>45</td>
<td>2.6</td>
<td>Risk factor Self-reported physician diagnosed or use of medications, or clinical diagnosis with WHO 85 (only FPG*)</td>
<td></td>
</tr>
<tr>
<td>Warne (48)</td>
<td>Pima Study, United States (Pima)</td>
<td>1988</td>
<td>1-6</td>
<td>1 visit</td>
<td>NDM</td>
<td>733</td>
<td>≥18</td>
<td>40</td>
<td>35.0</td>
<td>Exposure Clinical diagnosis with WHO 85</td>
<td></td>
</tr>
<tr>
<td>Burke (47)</td>
<td>Mexico City Diabetes Study, Mexico (MCDS)</td>
<td>1984</td>
<td>6</td>
<td>1 visit</td>
<td>NDM</td>
<td>1,754</td>
<td>35-64</td>
<td>24</td>
<td>12.1-22.9</td>
<td>Confounder Clinical diagnosis with WHO 85, or self-reported physician diagnosed and use of medications</td>
<td></td>
</tr>
<tr>
<td>San Antonio Heart Study, United States (SAHS)</td>
<td></td>
<td>1988</td>
<td>1-6</td>
<td>1 visit</td>
<td>NDM</td>
<td>7</td>
<td>246</td>
<td>27</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daimon (49)</td>
<td>Funagata Study, Japan (Funagata)</td>
<td>1995-1997</td>
<td>5</td>
<td>1 visit</td>
<td>NDM</td>
<td>978</td>
<td>59</td>
<td>79</td>
<td>3.7</td>
<td>Confounder Clinical diagnosis with WHO 85</td>
<td></td>
</tr>
<tr>
<td>Nauck (50)</td>
<td>Gottingen’s first-degree relatives, Germany (Gottingen)</td>
<td>1967</td>
<td>25</td>
<td>1 visit, 1 survey</td>
<td>NDM and first-degree family history</td>
<td>135</td>
<td>64</td>
<td>54</td>
<td>12.4</td>
<td>Risk factor Clinical diagnosis with WHO 85</td>
<td></td>
</tr>
<tr>
<td>Chen (51)</td>
<td>Penghu Study, Taiwan (Penghu)</td>
<td>1995</td>
<td>3</td>
<td>1 visit</td>
<td>NDM</td>
<td>600</td>
<td>60</td>
<td>52</td>
<td>14.4</td>
<td>Confounder Clinical diagnosis with ADA 97*</td>
<td></td>
</tr>
<tr>
<td>Spranger (52)</td>
<td>European Prospective Investigation into Cancer and Nutrition-Potsdam Study, Europe (EPIC-Potsdam)</td>
<td>1994-1998</td>
<td>4</td>
<td>1 visit</td>
<td>NDM</td>
<td>565</td>
<td>35-65</td>
<td>59</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laaksonen (53)</td>
<td>Kuopio Ischemic Heart Disease Risk Factor Study, Finland (KIHDRF)</td>
<td>1988-1989</td>
<td>4</td>
<td>1 visit</td>
<td>NDM</td>
<td>907</td>
<td>42-62</td>
<td>100</td>
<td>14.1</td>
<td>Risk factor Clinical diagnosis with ADA 97 or use of medications</td>
<td></td>
</tr>
<tr>
<td>Harding (54)</td>
<td>European Prospective Investigation into Cancer and Nutrition-Norfolk Study, Europe (EPIC-Norfolk)</td>
<td>1993-1997</td>
<td>3-7</td>
<td>1 survey, 1 visit</td>
<td>NDM, NCHD, and NC</td>
<td>21,472</td>
<td>40-74</td>
<td>45</td>
<td>Men: 4.1 Women: 2.4</td>
<td>Confounder Self-reported physician diagnosed with no insulin prescribed within the first year following diagnosis and/or an HbA1c level greater than 7% at baseline or follow-up visit, general practice diabetes register, hospital diabetes register, death certificates</td>
<td></td>
</tr>
<tr>
<td>Rodríguez-Moran (55)</td>
<td>Durango, Mexico (Durango)</td>
<td>1997</td>
<td>2</td>
<td>1 visit</td>
<td>NDM</td>
<td>72</td>
<td>≥30</td>
<td>43</td>
<td>48.6</td>
<td>Confounder Clinical diagnosis with ADA 97</td>
<td></td>
</tr>
<tr>
<td>Edelstein (56)</td>
<td>Baltimore Longitudinal Study of Aging, United States (BLSA)</td>
<td>1964</td>
<td>1-9</td>
<td>2-8 visits</td>
<td>IGT*</td>
<td>675</td>
<td>59</td>
<td>74</td>
<td>35.8</td>
<td>Risk factor Clinical diagnosis with WHO 85, use of medications, physician diagnosis (RBS* only)</td>
<td></td>
</tr>
<tr>
<td>Rancho Bernardo Study, United States (RBS)</td>
<td>1984-1987</td>
<td>7-9</td>
<td>1 visit</td>
<td>IGT</td>
<td>186</td>
<td>68</td>
<td>35</td>
<td>40</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nauru Study, Nauru (Nauru)</td>
<td>1987</td>
<td>5-12</td>
<td>2-4 visits</td>
<td>IGT</td>
<td>305</td>
<td>37</td>
<td>46</td>
<td>62.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>San Luis Valley Diabetes Study, United States (SLVDS)</td>
<td>1984-1988</td>
<td>1-3</td>
<td>2-4 visits</td>
<td>IGT</td>
<td>177</td>
<td>60</td>
<td>40</td>
<td>72.9</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* NDM, non-diabetes mellitus; NCHD, non-coronary heart disease; WHO 85, World Health Organization 1985 criteria (59); NC, noncancer; WHO 80, World Health Organization 1980 criteria (58); WHO 99, World Health Organization 1999 criteria (60); NGT, normal glucose tolerance; FPG, fasting plasma glucose; ADA 97, American Diabetes Association 1997 criteria (57); HbA1c, hemoglobin A1c; IGT, impaired glucose tolerance; RBS, Rancho Bernardo Study.
However, some have argued against the use of waist/hip ratio as a measure of obesity because of its ambiguous biologic interpretation, its lesser sensitivity to weight gain, its greater variability across age, sex, and ethnic groups, and its greater computational complexity and interpretation in a public health context (2).

TABLE 3. Incident diabetes rate, mean and standard deviation of body mass index, waist circumference, and waist/hip ratio by region and overall for studies between 1985 and 2004 included in the meta-analysis

<table>
<thead>
<tr>
<th>Region</th>
<th>Incident diabetes rate/1,000 person-years (geometric mean)</th>
<th>Body mass index (kg/m²)</th>
<th>Waist circumference (cm)</th>
<th>Waist/hip ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>Standard deviation</td>
<td>Mean</td>
</tr>
<tr>
<td>Asia</td>
<td>5.2</td>
<td>24.2</td>
<td>3.1</td>
<td>79.7</td>
</tr>
<tr>
<td>Europe</td>
<td>7.2</td>
<td>26.3</td>
<td>3.4</td>
<td>92.1</td>
</tr>
<tr>
<td>United States</td>
<td>13.5</td>
<td>26.6</td>
<td>4.5</td>
<td>88.2</td>
</tr>
<tr>
<td>Overall</td>
<td>25.8</td>
<td>25.8</td>
<td>4.3</td>
<td>87.2</td>
</tr>
</tbody>
</table>

FIGURE 2. Forest plot of the association between body mass index (BMI) and incident diabetes (95% confidence interval) for 32 studies published between 1985 and 2004. The pooled relative risk per standard deviation (SD: 4.3) (plotted as diamond) is 1.87 (95% confidence interval: 1.67, 2.10). NAS, Normative Aging Study; NHANES I, First National Health and Nutrition Examination Survey; SAHS, San Antonio Heart Study; IOWA, Iowa Women’s Health Study; N-NCCS, Northern Native Canadian Cohort Study; FINRISK, Finland study; MHPS, Male Health Professionals Study; NHS, Nurses’ Health Study; ARIC, Atherosclerosis Risk in Communities Study; IRAS, Insulin Resistance Atherosclerosis Study; JACDS, Japanese-American Community Diabetes Study; MCDS, Mexico City Diabetes Study; SA, San Antonio; EPIC, European Prospective Investigation into Cancer and Nutrition; KIHDRF, Kuopio Ischemic Heart Disease Risk Factor Study; BLSA, Baltimore Longitudinal Study of Aging; RBS, Rancho Bernardo Study; SLVDS, San Luis Valley Diabetes Study.

FIGURE 3. Forest plot of the association between waist circumference (WC) and incident diabetes (95% confidence interval) for 18 studies published between 1985 and 2004. The pooled relative risk per standard deviation (SD: 11.6) (plotted as diamond) is 1.87 (95% confidence interval: 1.58, 2.20). NAS, Normative Aging Study; IRAS, Insulin Resistance Atherosclerosis Study; JACDS, Japanese-American Community Diabetes Study; MCDS, Mexico City Diabetes Study; SA, San Antonio; KIHDRF, Kuopio Ischemic Heart Disease Risk Factor Study; BLSA, Baltimore Longitudinal Study of Aging; RBS, Rancho Bernardo Study; SLVDS, San Luis Valley Diabetes Study.
In the present analysis, we have compared the associations across the obesity indicators by focusing on the difference between risk ratios. Several other strategies are possible to compare the performance of disease markers, such as measures of predictive power (likelihood measures) or measures of discriminatory performance, such as the area under the receiver-operating characteristic curve. For example, Stevens et al. (15) found that waist circumference had better discriminatory performance for diabetes than did body mass index or waist/hip ratio.

A potential problem that arises in meta-analyses of observational data, such as this one, is that the findings may appear to be very precise but are simply reinforcing biases present in individual studies. In addition, although an individual study may report an “un-confounded” estimate of an association, associations may differ between studies because of different distributions of the obesity indicator and the confounding variables or because of differences in the mechanism in biologic action across populations (67).

The necessity to investigate heterogeneity in meta-analyses of observational studies is well recognized (68). We investigated the role of study-level characteristics and found only two characteristics that affected the strength of the association: incident diabetes rate and study inclusion criteria. A smaller relative risk in studies with a higher incident diabetes rate or higher baseline glucose levels may be explained by study-level confounding or a different mechanism of biologic action between obesity and diabetes in those populations where diabetes is more prevalent. We found few differences in the relative risk of the three obesity indicators for each population group. Only for Asia do body mass index and waist circumference seem to have a stronger association than does waist/hip ratio with incident diabetes.

We hypothesized that associations may be heterogeneous, reflecting different underlying causes of overweight, genetic predisposition, and obesity distribution.

When comparing differences between obesity indicators across study-level characteristics, we found that the present analysis had several limitations. Comparisons of waist circumference and body mass index or of waist/hip ratio and body mass index were not based on the same set of studies. In the case of body mass index, the estimated relative risk for the full set of studies was different from the estimated relative risk based on the subset of studies used for the pairwise comparisons with waist circumference and

<table>
<thead>
<tr>
<th>Obesity indicator</th>
<th>No. of studies</th>
<th>Pooled relative risk</th>
<th>95% confidence interval</th>
<th>Standard deviation</th>
<th>Between-study heterogeneity ($I^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All studies</td>
<td>32</td>
<td>1.87</td>
<td>1.67, 2.10</td>
<td>4.3</td>
<td>95.5</td>
</tr>
<tr>
<td>Studies with waist circumference</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waist circumference</td>
<td>18</td>
<td>1.87</td>
<td>1.58, 2.20</td>
<td>11.6</td>
<td>93.3</td>
</tr>
<tr>
<td>Body mass index</td>
<td></td>
<td>1.72</td>
<td>1.47, 2.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Studies with waist/hip ratio</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waist/hip ratio</td>
<td>25</td>
<td>1.88</td>
<td>1.61, 2.19</td>
<td>0.07</td>
<td>96.2</td>
</tr>
<tr>
<td>Body mass index</td>
<td></td>
<td>1.98</td>
<td>1.70, 2.30</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
waist/hip ratio. The differences seen in the estimated relative risk between subsets may be due to differences in the study characteristics (study-level confounding) and random variation. When we performed ecologic comparisons, studies included in the analysis were not the same for all three obesity indicators, potentially introducing study-level confounding. Sparseness of studies in each category did not allow us to further analyze the heterogeneity with

![FIGURE 5. Pooled relative risk (95% confidence interval) for body mass index (BMI) with incident diabetes from the meta-analysis of studies published between 1985 and 2004, stratified by study-level population characteristic: gender, diabetes rate, inclusion criteria, age, general obesity, and region. DM, diabetes mellitus; NDM, non-diabetes mellitus; NCHD, non-coronary heart disease; IGT, impaired glucose tolerance; NGT, normal glucose tolerance; SD, standard deviation.](https://academic.oup.com/epirev/article-abstract/29/1/115/441437)

![FIGURE 6. Pooled relative risk (95% confidence interval) for waist circumference (WC) with incident diabetes from the meta-analysis of studies published between 1985 and 2004, stratified by study-level population characteristic: gender, diabetes rate, inclusion criteria, age, general obesity, and region. DM, diabetes mellitus; NDM, non-diabetes mellitus; NCHD, non-coronary heart disease; IGT, impaired glucose tolerance; BMI, body mass index; SD, standard deviation.](https://academic.oup.com/epirev/article-abstract/29/1/115/441437)
a multivariable approach. Additional heterogeneity may be derived from diversity of design features, clinical characteristics, and model assumptions. Importantly, study-level characteristics are ecologic and may not reflect the relative risks between subgroups formed across individuals within a study.

Although it is important to summarize the existing literature, the present meta-analysis suffers from having to work with the data as they were reported. In addition, for the relative risk to be obtained, assumptions had to be made regarding the distribution of the three anthropometric indicators and the correlation of the estimates across
anthropometric categories. A more detailed approach can be performed with meta-analysis of data on individual participants.

The Collaborative Study of Obesity and Diabetes in Adults (CODA) project has been established to answer some of these questions. This project has collected data on individual participants from 37 studies worldwide (69). Preliminary results presented at the American Diabetes Association’s 64th Scientific Sessions (63) were similar to those found in the present literature-based meta-analysis, that waist circumference is a slightly better predictor of diabetes than is body mass index: 

\[
RR_{WC} = 2.1, 95\% \text{ CI: 1.9, 2.3}; \quad RR_{BMI} = 1.9, 95\% \text{ CI: 1.7, 2.0}.
\]

The estimated relative risks from the data on individual participants were slightly higher than those observed in this literature-based meta-analysis. We hypothesize that the difference in the estimated relative risk may be explained because different sets of studies were analyzed in each project, producing random variation and study-level confounding, in addition to any bias introduced by our analytical approach.

In conclusion, despite the largely unexplained heterogeneity of relative risk, the present study demonstrated consistently strong associations of body mass index, waist circumference, and waist/hip ratio with incident diabetes. Although the clinical appeal of use of a measure of visceral fat is undeniable, the statistical reality is that waist circumference and body mass index are very highly correlated and likely to behave similarly in diabetes prediction. Waist/hip ratio, despite lower correlation with body mass index and waist circumference, appears to have the same ability to predict diabetes as do both body mass index and waist circumference. Additional insight into these issues will be gained by a meta-analysis of data on individual participants, such as the Collaborative Study of Obesity and Diabetes in Adults project is currently undertaking.

ACKNOWLEDGMENTS

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Conflict of interest: none declared.

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60. Definition, diagnosis and classification of diabetes mellitus and its complications. Part 1: diagnosis and classification of


