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Use of height^3:waist circumference^3 as an index for metabolic risk assessment?

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Current anthropometric indices for health risk assessment are indirect measures of total or visceral body fat mass that do not consider the inverse relationship of lean body mass to metabolic risk as well as the non-linear relationship between central obesity and insulin resistance. We examined a new anthropometric index that reflects the relationship of waist circumference (WC) as a risk factor to fat-free mass (FFM) as a protective parameter of body composition. In a population of 335 adults (191 females and 144 males; mean age 53 (SD 13·9) years) with a high prevalence of obesity (27 %) and metabolic syndrome (30 %) we derived FFM:WC^3 from the best fit of the relationship with metabolic risk factors (plasma triacylglycerol levels and insulin resistance by homeostasis model assessment index). Because FFM is known to be proportional to the cube of height, FFM was subsequently replaced by height^3 yielding height^3:WC^3 as an easily applicable anthropometric index. Significant inverse relationships of height^3:WC^3 to metabolic risk factors were observed for both sexes. They slightly exceeded those of conventional anthropometric indices such as BMI, WC or WC:hip ratio in women but not in men. The exponential character of the denominator WC^3 implies that at a given FFM with gradually increasing WC the increase in metabolic risk is lower than proportional. Further studies are needed to evaluate height^3:WC^3 as an anthropometric index for health risk assessment.

Obesity: Metabolic risk: Anthopometric indices: Waist circumference: Fat-free mass: Height

BMI has been and still remains the most popular anthropometric index of body fat mass (FM). Although unreliable in individuals (Piers *et al.* 2000), BMI shows a good relationship with health risk at the population level which is not inferior to the direct assessment of FM (Terry *et al.* 1989; Richelsen & Pedersen, 1995; Warne *et al.* 1995; Tai *et al.* 1999; Nakanishi *et al.* 2000; Tulloch-Reid *et al.* 2003). Today, abdominal or visceral obesity is considered more important than total body FM. Therefore waist circumference (WC) has become the favourite anthropometric index for health risk assessment. WC was found to be closely associated with insulin resistance and CVD (Janssen *et al.* 2004; Lofren *et al.* 2004) and is used in several definitions of the metabolic syndrome: European Group for the Study of Insulin Resistance (Balkau & Charles, 1999), Adult Treatment Panel III (Expert Panel on Detection, Evaluation, and Treatment of High Blood Cholesterol in Adults, 2002) and International Diabetes Federation (2005).

The idea that not only the total amount of FM but also body fat distribution matters also underlies the WC:hip ratio (Ashwell *et al.* 1978), but this index provides no information about the total amount of visceral FM. However, independent from FM, hip or thigh circumferences are inversely associated with health risk (Seidell *et al.* 1997, 2001; Lissner *et al.* 2001; Bigaard *et al.* 2003; Chan *et al.* 2003; Snijder *et al.* 2003). Because this observation is likely to be explained by muscle mass in the gluteofemoral region that reflects whole body lean mass, a new aspect of the WC:hip ratio is the relationship of WC as a risk factor to a protecting and thus compensating body compartment that is fat-free mass (FFM). FFM is well known to be inversely related to all-cause mortality (Heitmann *et al.* 2000; Allison *et al.* 2002; Bigaard *et al.* 2004*a*,*b*). The K-rich active lean mass was also positively related to life expectancy (Kotler *et al.* 1985) as well as fitness (Hansen & Allen, 2002).

In addition to hip circumference, height was shown to be an excellent index for lean body mass (Forbes, 1974). This might also explain why some authors observed a closer association of WC:height ratio to cardiovascular risk factors when compared with WC alone (Hara *et al.* 2002; Hsieh *et al.* 2003; Hsieh and Muto 2005; Sayeed *et al.* 2003). Also height partly explained the inverse associations of hip circumference with diabetes, dyslipidaemia or hypertension (Snijder *et al.* 2004). However, a simple WC:height or WC:hip ratio may be inappropriate to account for a protective effect of FFM

Abbreviations: AUC, area under the curve; FFM, fat-free mass; FM, fat mass; HDL-C, HDL-cholesterol; HOMA-IR, insulin resistance by homeostasis model assessment; ROC, receiver operating characteristic; TG, triacylglycerol; WC, waist circumference.

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since FFM is better represented by height^3 than by height (Forbes, 1974) or hip circumference.

An additional aspect which is not adequately reflected by currently available obesity indices might be a non-linear relationship between WC and metabolic risk. This is supported by the finding that the correlation between visceral adipose tissue and insulin sensitivity (measured by the clamp technique) can be better described by non-linear than by linear models (Gan *et al.* 2003). Consistent with this observation, small increases in the intra-abdominal fat area are associated with larger reductions in insulin sensitivity when small amounts of intra-abdominal fat are present and this effect diminishes as intra-abdominal fat accumulates (Cnop *et al.* 2002). Thus, we may speculate that only a non-linear relationship between WC as a risk factor and FFM may be linearly related to insulin resistance as a central metabolic disturbance.

In the present study we aimed to examine a new anthropometric index for health risk assessment that considers three aspects: (a) the relationship of a risk factor (WC) to a protective and compensating body compartment (FFM); (b) a non-linear relationship between FFM and WC; (c) the substitution of FFM by height^3 in order to generate an easy-to-apply anthropometric index.

The relationship between the new anthropometric index and metabolic risk factors was then compared with conventional anthropometric indices of health risk assessment.

Subjects and methods

Study population and design

The study sample was taken from adults of the Kiel Obesity Prevention Study – Family Study (Danielzik *et al.* 2004). The main objective of this ongoing three-generation trial is to assess the contribution of genetic factors to the metabolic syndrome. In all, 335 subjects (191 women and 144 men) were recruited by advertisements in local newspapers, by notice-board postings and writing to families that are continuously followed up as a Kiel Obesity Prevention Study subcohort. Inclusion criteria for study participation are at least two grandparents taking part as well as one family member with overweight or obesity. All participants were of Caucasian descent.

The study protocol was approved by the local ethical committee of the Christian-Albrechts-Universität (Kiel, Germany). Each subject provided informed written consent before participation.

Anthropometric measurements and body composition analysis

Body weight was measured to the nearest 0·1 kg on an electronic scale coupled to the BOD-POD® Body Composition System (Life Measurement Instruments, Concord, CA, USA). Height was measured on a stadiometer to the nearest 0·5 cm. WC was measured to the nearest 0·5 cm midway between the lowest rib and the iliac crest while the subject was at minimal respiration. Air-displacement plethysmography was performed by the BOD-POD® device as described in detail elsewhere (Bosy-Westphal *et al.* 2003*b*). Briefly, subjects were measured in tight-fitting underwear and a swimming cap. Two repeated measurements of body volume were performed and averaged. Measured thoracic lung volume was subtracted from body volume. BOD-POD® software was used to calculate body density as body weight divided by body volume and FM percentage using Siri's equation (Siri, 1961). FFM (kg) was calculated according to weight (kg) – FM (kg).

Metabolic variables

Blood pressure measurements were obtained with the subject in a seated position by using a standard manual sphygmomanometer. Blood samples were obtained after a minimum 8 h fast and metabolic parameters were analysed by standard procedures. Briefly, plasma glucose was assayed by using a hexokinase enzymic method. Cholesterol and triacylglycerol (TG) concentrations were measured enzymically by hydrolysing cholesteryl ester and TG to cholesterol and glycerol, respectively. HDL-cholesterol (HDL-C) was analysed in the supernatant fraction after precipitation of lipoproteins. Plasma insulin was measured by immunoradiometric assay (all kits and standards by Konelab-Cooperation, Espoo, Finland). The homeostasis model assessment (Matthews *et al.* 1985) was used to calculate insulin resistance (IR) according to the equation: insulin resistance by homeostasis model assessment (HOMA-IR) = fasting insulin (μU/ml) × fasting glucose (mmol/l)/22·5. HOMA-IR was not calculated for subjects with fasting glucose level $>7{\cdot}0$ mmol/l or subjects using oral anti-diabetics or insulin. C-reactive protein was measured turbidimetrically using a latex-agglutination test with a sensitivity of 0·1 mg/l and a between-day precision of better than 1·9 % CV (CRP-Dynamik Hit917; Biomed Labordiagnostik GmbH, Oberschleißheim, Germany). Uric acid was measured by an enzymic colorimetric test with a sensitivity of 2 mg/l and a between-day precision better than 1·7 % CV (UA plus kit; Roche Diagnostics GmbH, Mannheim, Germany).

Metabolic syndrome was defined according to the National Cholesterol Education Program Adult Treatment Panel III report (Expert Panel on Detection, Evaluation, and Treatment of High Blood Cholesterol in Adults, 2002) as three or more of the following characteristics: (1) hypertriacylglycerolaemia: ≥ 1500 mg/l ($\geq 1{\cdot}69$ mmol/l); (2) low HDL-C: <400 mg/l ($<1{\cdot}04$ mmol/l) in men or <500 mg/l ($<1{\cdot}29$ mmol/l) in women; (3) high blood pressure: $\geq 130/85$ mmHg; (4) high fasting plasma glucose: ≥ 1100 mg/l ($\geq 6{\cdot}1$ mmol/l); (5) abdominal obesity – WC >88 cm in women, and >102 cm in men. Participants who reported a history of physician-diagnosed diabetes, hypertension or hyperlipidaemia and taking antihypertensive (14·8 %), anti-diabetic (insulin or oral agents) (2·7 %) or lipid-lowering drugs (5·4 %) were defined as hypertensive, hyperglycaemic or hyperlipidaemic respectively. Respective data from these subjects were excluded from descriptive statistics as well as from analyses of continuous variables.

Statistical analyses

All analyses were conducted using SPSS 13.0 for Windows software (SPSS Inc., Chicago, IL, USA). Descriptive statistics are given as mean values and standard deviations. TG, C-reactive protein, insulin and HOMA-IR were

normalised by logarithmic transformation. ANOVA was used to compare means between sexes. Pearson correlation coefficients were calculated and partial correlation coefficients were calculated and adjusted for age. Separate analyses were performed for men and women due to possible differences in effects of body size and body composition on metabolic risk. Accordingly we observed significant interaction terms between sex and obesity indices in the relationship with several metabolic risk factors. To study the association of anthropometric indices and body composition (independent variables) with metabolic risk factors (dependent variables), stepwise multiple regression analysis was performed. Effect modification by sex and age was evaluated by adding product terms to the model.

To test the hypothesis that it is the combination of height^3 and WC^3 that influences metabolic risk (the interaction between the two), we expressed height^3:WC^3 as height$^3 \times (\mathrm{WC}^3)^{-1}$ and tested the interaction hypothesis by simultaneously regressing the dependent variables (for example, ln-HOMA-IR and ln-TG) on the two main effects (height^3 and WC^3) and the product term (height$^3 \times (\mathrm{WC}^3)^{-1}$). If the regression coefficient for the product term is significantly different from zero, one can conclude that the multiplicative combination height$^3 \times (\mathrm{WC}^3)^{-1}$ has some influence on morbidity above and beyond the single effects of height^3 or $(\mathrm{WC}^3)^{-1}$ or their additive combination (Kronmal, 1992; Allison *et al.* 1995). P values $<0{\cdot}05$ were considered to be statistically significant.

To evaluate the accuracy of obesity indices for assessment of metabolic risk we calculated sensitivity (proportion of true positives, i.e. cases correctly identified as having an elevated risk factor for example, HOMA-IR) and specificity (proportion of true negatives, i.e. proportion of cases correctly identified as not having an elevated HOMA-IR) of obesity indices for creation of areas under the receiver operating characteristic (ROC) curves. The ROC curve is a plot of sensitivity (true positive fraction) *v.* 1 – specificity (false positive fraction) for a predictor. The area under the ROC curve provides a single measure of overall accuracy that is not dependent upon a particular threshold. A web-based calculator for area under the curve (AUC) of ROC curves was used (Eng, 2002). Cut-offs for obesity indices were chosen as previously described (Bosy-Westphal *et al.* 2006). For height^3:WC^3, cut-offs used in both sexes were: $<3{\cdot}03$, $<4{\cdot}115$, $<5{\cdot}18$, $<6{\cdot}245$, $<7{\cdot}31$, $<8{\cdot}375$, $<9{\cdot}44$, $<10{\cdot}505$, $<11{\cdot}57$ and $<12{\cdot}635$.

Results

Characteristics of the study population

Subjects' characteristics regarding age, body composition and metabolic risk profile are given in Table 1. According to the BMI cut-off of 30 kg/m^2, fifty-five females (28·8 %) and thirty-five males (24·3 %) were obese. Women had significantly lower stature, FFM, WC and WC:hip ratio but higher percentage FM than men. Sex differences in metabolic risk factors were observed for HDL-C (with higher values in women) and uric acid (with higher values in men). The prevalence of metabolic syndrome according to NCEP criteria was 30·4 % in women and 29·9 % in men, respectively.

Development of a new anthropometric index

The ratio FFM:WC^3 was derived from the best fit with ln-TG levels (r 0·44; $P<0{\cdot}001$) and ln-HOMA-IR (r 0·52; $P<0{\cdot}001$). Mean values for FFM:WC^3 were 66·6 (SD 26·3) kg/m^3 in women and 69·2 (SD 22·2) kg/m^3 in men. Substituting FFM by height^3 yielded height^3:WC^3. Mean values for height^3:WC^3

Table 1. Characteristics of the study population (Mean values and standard deviations)

	Total (n 335)		Females (n 191)		Males (n 144)	
	Mean	SD	Mean	SD	Mean	SD
Age (years)	53·5	13·9	53·9	14·1	53·0	13·7
Height (cm)	170·6	9·9	164·5	6·9	178·7***	7·1
BMI (kg/m^2)	27·8	4·9	27·9	5·5	27·7	4·1
FFM (kg)	52·7	12·0	44·8	7·0	63·2***	8·8
FM (%)	34·8	9·5	39·8	7·8	28·2***	7·5
WC (cm)	94·2	13·8	90·7	14·5	98·8***	11·3
WC:hip (cm/cm)	0·91	0·08	0·87	0·06	0·96***	0·06
WC:height (cm/cm)	0·55	0·08	0·55	0·09	0·55	0·07
Glucose (mmol/l)	5·45	1·09	5·36	1·14	5·56	1·01
Insulin (mU/l)	14·65	10·91	14·94	11·42	14·27	10·24
HOMA-IR (mU/l × mmol/l)	3·45	2·93	3·46	2·86	3·45	3·04
TG (mg/l)	1156·9	643·4	1115·7	581·8	1213·2	718·0
Cholesterol (mg/l)	2157·0	423·8	2168·5	464·8	2141·3	361·4
HDL-C (mg/l)	522·2	151·4	556·2	149·7	475·6***	141·5
Uric acid (mg/l)	52·4	13·6	48·0	11·9	58·0***	13·7
CRP (mg/l)	3·18	6·51	3·31	6·64	3·03	6·37
BPsys (mmHg)	132·5	20·4	130·2	21·1	135·3*	19·2
BPdias (mmHg)	82·6	10·1	81·9	10·1	83·5	10·0

FFM, fat-free mass measured by air-displacement plethysmography; FM, fat mass measured by air-displacement plethysmography; WC, waist circumference; HOMA-IR, homeostasis model assessment of insulin resistance; TG, triacylglycerols; CRP, C-reactive protein; BPsys, systolic blood pressure; BPdias, diastolic blood pressure.
Mean value was significantly different from that for females: *$P<0{\cdot}05$, ***$P<0{\cdot}001$ (ANOVA).

were 6·88 (SD 3·14) cm^3/cm^3 in women and 6·39 (SD 2·29) cm^3/cm^3 in men.

Associations between anthropometric indices, body composition and age

Fig. 1 shows a closer relationship between height^3 (m^3) and FFM (kg) than between hip circumference (cm) and FFM (kg) for men and women separately as well as for both sexes combined. In Table 2, the correlation matrix between anthropometric variables, body composition and age is given for men and women separately. Most anthropometric indices were highly correlated to each other in both sexes. The high correlation coefficients observed between FFM:WC^3, height^3:WC^3 and WC:height in both sexes suggest an interchangeable use of these anthropometric indices, but the relationship between WC:height and height^3:WC^3 is non-linear. With the exception of percentage FM and WC in men, all anthropometric indices correlated with age.

Associations between anthropometric indices, body composition and metabolic risk

In Table 3 partial correlations corrected for age describe the relationships between anthropometric variables, body composition and metabolic risk factors for the whole group as well as separately for women and men. In the whole group of subjects, there were significant age-adjusted partial correlations between FFM and systolic blood pressure (r 0·23; $P<0·001$), diastolic blood pressure (r 0·21; $P<0·01$), HDL-C (r −0·34; $P<0·001$), fasting plasma glucose (r 0·16; $P<0·01$), uric acid (r 0·45; $P<0·001$), ln-TG (r 0·18; $P<0·01$) and ln-HOMA-IR (r 0·15; $P<0·05$). Significant age-adjusted partial correlations with height were observed for systolic blood pressure (r 0·19; $P<0·01$), diastolic blood pressure (r 0·16; $P<0·05$), HDL-C (r −0·22; $P<0·001$) and uric acid (r 0·28; $P<0·001$), respectively.

For both sexes combined as well as in the subgroup of women, FFM:WC^3 or height^3:WC^3 were most closely related to metabolic risk profile. In the subgroup of men, WC and height^3:WC^3 were inversely but similarly closely associated to metabolic risk profile (with the exception of blood pressure and fasting glucose concentrations). The relationships of FFM:WC^3 and height^3:WC^3 with ln-TG levels or HOMA-IR are plotted in Fig. 2. In Table 4 the contributions of height^3:WC^3 and the conventional index WC to variance explanation in metabolic risk were compared by calculating two separate stepwise regression analyses including either WC or height^3:WC^3 as well as age and sex as independent variables. With the exception of HDL-C, uric acid levels and systolic blood pressure, the contribution of height^3:WC^3 to variance explanation in metabolic risk independent of age and sex was slightly higher than for WC. In additional multiple regression analyses only the interaction term height$^3 \times (\mathrm{WC}^3)^{-1}$ but not the two main effects of height^3 and $(\mathrm{WC}^3)^{-1}$ were independent predictors of all metabolic risk factors. In Table 5 the accuracy of obesity indices percentage FM, BMI, WC, WC:hip, WC:height and height^3:WC^3 with respect to the prediction of elevated HOMA-IR ($>2·61$ mU/l × mmol/l) is compared by using ROC analysis. AUC values for both sexes and different obesity indices were all in a similar range. However, AUC of height^3:WC^3 reached values of 0·75 in women and 0·84 in men that slightly exceeded the values of the other obesity indices. Non-overlapping 95 % CI of these AUC indicate significant differences in sensitivity and specificity of height^3:WC^3 when compared with conventional obesity indices. ROC analyses were also performed for other metabolic risk factors, i.e. low HDL-C, elevated blood pressure and TG levels (data not shown). AUC values for height^3:WC^3 exceeded those of conventional obesity indices for the prediction of low HDL-C in women (AUC = 0·721) and elevated TG in men (AUC = 0·741), respectively. By contrast, for prediction of elevated blood pressure in both sexes, elevated TG levels in women and low HDL-C in men, the accuracy of WC:height was higher when compared with all other obesity indices.

Discussion

Contribution of height or fat-free mass to metabolic risk

Anthropometric indices have long been used for health risk assessment. The Belgian statistician A. J. Quetelet found out that shape, density and proportions of the body all vary with height. In children, body mass increases in approximate proportion to the cube of height. Therefore the ponderal index

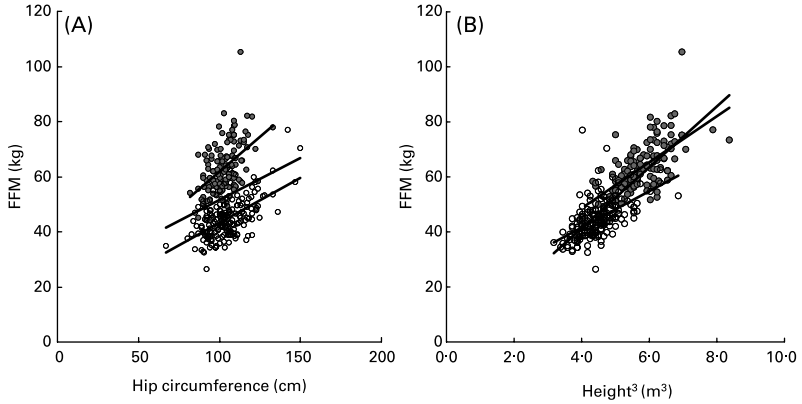

Fig. 1. (A) Regression of fat-free mass (FFM; measured by air-displacement plethysmography) on hip circumference for men (●; $y = 0·5056x + 11·192$; R^2 0·23) and women (○; $y = 0·3273x + 10·591$; R^2 0·33) separately and for both sexes combined ($y = 0·307x + 20·816$; R^2 0·08). (B) Regression of FFM on height^3 for men ($y = 8·3701x + 15·126$; R^2 0·43) and women ($y = 6·5965x + 15·201$; R^2 0·30) separately and for both sexes combined ($y = 11·067x - 2·9046$; R^2 0·66).

Table 2. Pearson correlation coefficients between anthropometric variables, body composition and age for women (lower left-hand side) and men (upper right-hand side)

Men... Women	Age	Height	BMI	FFM	% FM	WC	WC:hip	WC:height	FFM:WC^3	Height^3:WC^3
Age	–	−0·51***	−0·02	−0·39***	0·16	0·15	0·24**	0·32***	−0·38***	−0·36***
Height	−0·39***	–	−0·02	0·65***	−0·15	0·06	−0·11	−0·28**	0·23**	0·28**
BMI	0·15*	−0·10	–	0·50***	0·69***	0·88***	0·52***	0·85***	−0·70***	−0·80***
FFM	−0·34***	0·55***	0·58***	–	−0·11	0·41***	0·10	0·17*	0·01	−0·15
% FM	0·43***	−0·17*	0·71***	−0·01	–	0·74***	0·56***	0·76***	−0·86***	−0·76***
WC	0·27***	0·02	0·91***	0·54***	0·70***	–	0·72***	0·94***	−0·87***	−0·89***
WC:hip	0·20**	−0·05	0·51***	0·28***	0·38***	0·73***	–	0·72***	−0·74***	−0·73***
WC:height	0·36***	−0·23**	0·91***	0·39***	0·73**	0·97***	0·72***	–	−0·91***	−0·94***
FFM:WC^3	−0·46***	0·18*	−0·78***	−0·21**	−0·84***	−0·89***	−0·69***	−0·91***	–	0·95***
Height^3:WC^3	−0·38***	0·26***	−0·83***	−0·31***	−0·74***	−0·89***	−0·69***	−0·93***	0·97***	–

FFM, fat-free mass measured by air-displacement plethysmography; FM, fat mass measured by air-displacement plethysmography; WC, waist circumference.
*$P<0·05$; **$P<0·01$; ***$P<0·001$.

that normalises body mass by height^3 (weight/height^3) is used in paediatrics. In adults, body mass increases in approximate proportion to the square of height presented by Quetelet's BMI (weight/height^2). More than 30 years ago, Gilbert B. Forbes showed that in adults lean body mass is proportional to the cube of height (Forbes, 1974); Fig. 1 shows that height^3 is closer related to FFM in both sexes than hip circumference.

The inverse contribution of lean body mass to metabolic risk (Heitmann *et al.* 2000; Allison *et al.* 2002; Bigaard *et al.* 2004*a,b*) makes height an interesting anthropometric parameter for health risk assessment. Short height that reflects a lower FFM was associated with increased risk for CHD and height had an inverse relationship with serum cholesterol and non-HDL-C in middle-aged men which was independent

Table 3. Partial correlations between anthropometric variables or body composition and metabolic risk factors after adjustment for age

	% FM	BMI	WC	WC:hip	WC:height	FFM:WC^3	Ht^3:WC^3
All							
Glucose	0·09	0·24***	0·26***	0·24***	0·26***	−0·23***	−0·25***
ln-Insulin	0·36***	0·45***	0·44***	0·29***	0·48***	−0·50***	−0·49***
ln-HOMA-IR	0·35***	0·49***	0·49***	0·31***	0·52***	−0·53***	−0·52***
ln-TG	0·22***	0·33***	0·37***	0·32***	0·36***	−0·40***	−0·41***
Cholesterol	0·13*	0·17**	0·15**	0·14*	0·17**	−0·17**	−0·17**
HDL-C	−0·02	−0·28***	−0·39***	−0·36***	−0·31***	0·31***	0·37***
Uric acid	−0·04	0·32***	0·44***	0·45***	0·34***	−0·29***	−0·37***
ln-CRP	0·26***	0·25***	0·20**	0·02	0·25***	−0·29***	−0·24***
BPsys	0·06	0·19**	0·23***	0·21***	0·17**	−0·19**	−0·20**
BPdias	0·14*	0·27***	0·25***	0·15*	0·20**	−0·23***	−0·26***
Women							
Glucose	0·07	0·16*	0·13	0·13	0·16*	−0·14	−0·17*
ln-Insulin	0·37***	0·44***	0·42***	0·32***	0·44***	−0·44***	−0·46***
ln-HOMA-IR	0·39***	0·49***	0·46***	0·33***	0·48***	−0·47***	−0·49***
ln-TG	0·24**	0·24**	0·26**	0·31***	0·30***	−0·35***	−0·36***
Cholesterol	0·16*	0·17*	0·17*	0·18*	0·19*	−0·18*	−0·19*
HDL-C	−0·23**	−0·31***	−0·36***	−0·33***	−0·34***	0·38***	0·40***
Uric acid	0·27**	0·43***	0·45***	0·35***	0·46***	−0·42***	−0·44***
ln-CRP	0·33***	0·30***	0·28**	0·12	0·29**	−0·31***	−0·28**
BPsys	0·18*	0·18*	0·14	0·14	0·15	−0·18*	−0·20*
BPdias	0·29**	0·31***	0·24**	0·16	0·24**	−0·27**	−0·31***
Men							
Glucose	0·37***	0·38***	0·45***	0·38***	0·45***	−0·40***	−0·38***
ln-Insulin	0·49***	0·47***	0·57***	0·51***	0·56***	−0·59***	−0·59***
ln-HOMA-IR	0·51***	0·52***	0·62***	0·50***	0·60***	−0·62***	−0·61***
ln-TG	0·43***	0·48***	0·52***	0·44***	0·50***	−0·49***	−0·50***
Cholesterol	0·1	0·12	0·13	0·25**	0·11	−0·11	−0·11
HDL-C	−0·25**	−0·26**	−0·29**	−0·15	−0·26**	0·25**	0·26**
Uric acid	0·22*	0·27**	0·28**	0·25*	0·26**	−0·25**	−0·28**
ln-CRP	−0·20*	0·17	0·17	0·06	0·19*	−0·23*	−0·22*
BPsys	0·20*	0·19*	0·24**	0·18	0·17	−0·20*	−0·16
BPdias	0·19*	0·20*	0·20*	0·08	0·12	−0·16	−0·14

FM, fat mass measured by air-displacement plethysmography; WC, waist circumference; FFM, fat-free mass measured by air-displacement plethysmography; HOMA-IR, homeostasis model assessment of insulin resistance; TG, triacylglycerols; HDL-C, HDL-cholesterol; CRP, C-reactive protein; BPsys, systolic blood pressure; BPdias, diastolic blood pressure.
*$P<0·05$; **$P<0·01$; ***$P<0·001$.

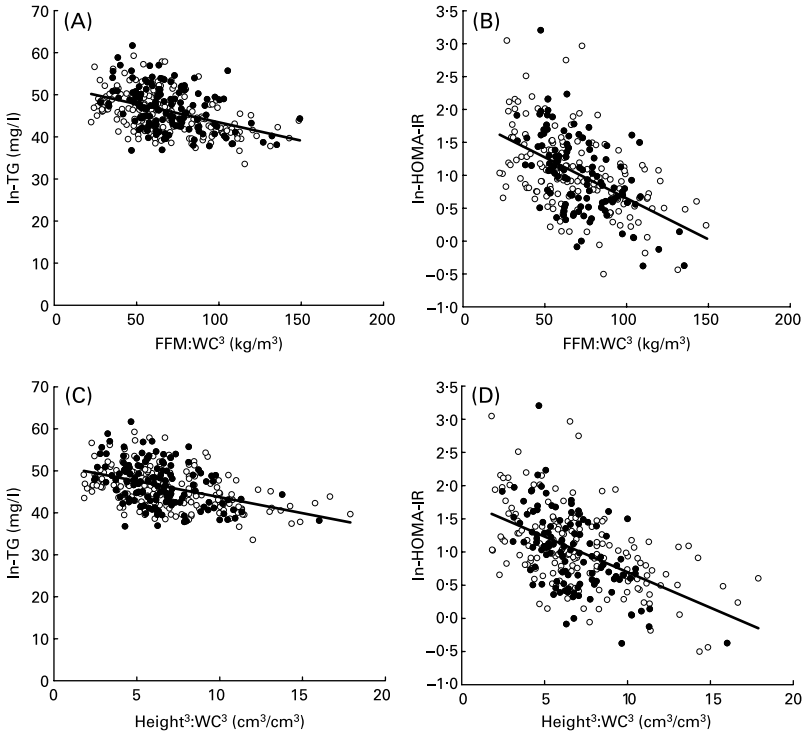

Fig. 2. Relationships between fat-free mass:waist circumference^3 (FFM:WC^3) and ln-triacylglycerol (TG) levels (A; $y = -0{\cdot}0087x + 5{\cdot}2133$; R^2 0·19) or homeostasis model assessment of insulin resistance (HOMA-IR) (B; $y = -0{\cdot}0125x + 1{\cdot}8972$; R^2 0·26) and between height^3:WC^3 and ln-TG levels (C; $y = -0{\cdot}0766x + 5{\cdot}1394$; R^2 0·19) or HOMA-IR (D; $y = -0{\cdot}1071x + 1{\cdot}7681$; R^2 0·27) for men (●) and women (○).

of BMI and WC:hip (Henriksson *et al.* 2001). We found positive correlations of height or FFM (kg) with uric acid and blood pressure and negative correlations of height or FFM (kg) with HDL-C (see p. 1215). Also in a multiple regression analysis we did not find an independent contribution of absolute amounts of FFM or height^3 to metabolic risk apart from height^3:WC^3, age and sex. These results are, however, not contradictory to a protective role of FFM regarding metabolic risk. First, it is obvious that overweight and obese individuals not only have larger amounts of FM but also larger amounts of absolute values of FFM. And second, we showed that in a multiple regression analysis only the height^3:WC^3 ratio (equal to the product term height^3 × (WC^3)$^{-1}$) but not the two main effects of height^3 and (WC^3)$^{-1}$ were independent predictors of metabolic risk factors (see p. 1215). Hence we can deduce that the height^3:WC^3 ratio reflects a 'special'

Table 4. Contributions of height^3:waist circumference (WC)^3 (model 1) or WC (model 2) to metabolic risk (explained variance by anthropometric index and by addition of sex and/or age)‡

	Model 1				Model 2			
			% Variance explained				% Variance explained	
	β	SEM	Height^3:WC^3	Sex and age	β	SEM	WC	Sex and age
Glucose, (mmol/l)	−0·12	0·02	9·4	10·4*	0·02	0·00	8·7	11·6*
ln-Insulin (mU/l)	−0·10	0·01	24·1	–	0·02	0·00	19·9	23·1†
ln-HOMA-IR (mU/l × mmol/l)	−0·11	0·01	27·2	–	0·02	0·00	25·1	27·6†
ln-TG (mg/l)	−0·08	0·1	20·1	–	0·01	0·00	15·7	17·4*
Cholesterol (mg/l)	−26·5	8·5	3·8	14·0*	4·7	1·7	2·2	13·4*
HDL-C (mg/l)	19·3	3·0	10·0	18·9*†	−3·7	6·0	13·1	17·7*†
Uric acid (mg/l)	−1·8	0·3	16·4	27·3†	0·04	0·1	21·1	27·2†
ln-CRP (mg/l)	−0·11	0·02	8·2	–	0·02	0·01	5·1	7·7†
BPsys (mmHg)	−1·34	0·41	3·2	25·0*†	0·32	0·08	4·2	25·0*†
BPdias (mmHg)	−0·94	0·21	11·6	15·8*	0·18	0·04	5·6	15·5*

HOMA-IR, homeostasis model assessment of insulin resistance; TG, triacylglycerols; HDL-C, HDL-cholesterol; CRP, C-reactive protein; BPsys, systolic blood pressure; BPdias, diastolic blood pressure.

* Significant independent contribution of age ($P < 0{\cdot}05$).

† Significant independent contribution of sex ($P < 0{\cdot}05$).

‡ Stepwise multiple regression analysis including metabolic risk factors as dependent variables and height^3:WC^3 (model 1) or WC (model 2); age and sex as independent variables.

Table 5. Areas under receiver operating characteristic curves (ROC AUC) showing sensitivity and specificity of fat mass measured by air-displacement plethysmography (FM), body mass index, was circumference (WC), WC:hip, WC:height and height^3:WC^3 in predicting elevated homeostasis model assessment of insulin resistance ($>2{\cdot}61$ mU/l × mmol/l)
(Areas under receiver operating characteristic curves and 95 % confidence intervals)

	Females		Males	
	ROC AUC	95 % CI	ROC AUC	95 % CI
% FM	0·642	0·636, 0·649	0·708	0·700, 0·717
BMI	0·642	0·634, 0·650	0·823	0·814, 0·832
WC	0·668	0·661, 0·675	0·686	0·668, 0·704
WC:hip	0·656	0·649, 0·663	0·755	0·747, 0·763
WC:height	0·730	0·724, 0·736	0·813	0·806, 0·820
Height^3:WC^3	0·750	0·744, 0·756	0·838	0·832, 0·844

aspect in explaining metabolic health risk that is not accounted for by either the numerator or denominator, individually or additively.

At a given WC, mortality rate ratio decreases with increasing BMI (Bigaard *et al.* 2003, 2004*a*,*c*). Thus, a protective effect of a high BMI at a given WC is likely to be due to a higher absolute amount of FFM. Different amounts of FFM per volume of visceral adipose tissue may also account for sex differences such as the finding that the relative risk of death from CVD is increased eight-fold in women with the highest WC:hip ratio (Lapidus *et al.* 1984) but only two-fold in men with the highest WC:hip ratio (Larsson *et al.* 1984). In women a lower visceral adipose tissue area than in men is associated with the same coronary risk (Onat *et al.* 2004). And comparing the amount of visceral adipose tissue at the sex-specific cut-offs for WC (>88 cm in women and >102 cm in men), visceral adipose tissue was found to be more than twice as high in men than in women (Kuk *et al.* 2005), suggesting that an equal health risk of both sexes at different WC cut-offs might be explained by a higher amount of protective muscle mass in men. However, in the subgroup of men, correlation analysis does not support an advantage of the height^3:WC^3 index when compared with the conventional WC (Table 3). By contrast, analysis of sensitivity and specificity for predicting elevated HOMA-IR revealed a higher ROC AUC for the height^3:WC^3 index when compared with the conventional indices for both sexes (Table 5).

Comparing parameters of body composition for health risk assessment

The association with parameters of body composition may be strong for some metabolic risk factors but weak for others. While there is a close association between WC or percentage FM and HOMA-IR or ln-TG, these associations are weaker for total cholesterol and blood pressure (Table 3). Additionally, different aspects of body composition may affect different types of risk factors. For example, central obesity (WC) is more closely related to ln-TG rather than general obesity because of a higher rate of flux of adipose tissue-derived NEFA to the liver from the splanchnic circulation (Aubert *et al.* 2003) or the non-splanchnic upper body fat (Guo *et al.* 1999). This leads to an increased production of TG-rich VLDL (Lewis *et al.* 1995). By contrast, ln-C-reactive protein is more closely related to general obesity (FM) presumably because macrophages within adipose tissue produce large amounts of IL-6 that stimulates CRP production in the liver (Wellen & Hotamisligil, 2003). The positive relationship observed between plasma uric acid levels and FFM or height supports the clinical observation that high muscle size was related to the incidence of gout in males (Brauer & Prior, 1978).

The plausibility of the close relationships between risk factors and WC:height (Table 3) that was also found by others (Hara *et al.* 2002; Hsieh *et al.* 2003; Hsieh and Muto 2005; Sayeed *et al.* 2003) remains unexplained, since height did not improve the prediction of intra-abdominal fat volume or cross-sectional intra-abdominal fat area in both sexes (Han *et al.* 1997). Considering the close relationship between WC:height and height^3:WC^3 (Table 2) there may be no statistical advantage of height^3:WC^3 over the simple WC:height ratio as a predictor of metabolic risk. The height^3:WC^3 ratio may thus add to our understanding of the metabolic and body compositional basis of the predictive value of the simple WC:height ratio. However, both ratios are not linearly related to each other and therefore cannot be used interchangeably. When comparing the accuracy of predicting elevated HOMA-IR, height^3:WC^3 in both sexes had a significantly higher ROC AUC than the conventional obesity indices percentage FM, BMI, WC, WC:hip and WC:height as indicated by the non-overlapping 95 % CI of these AUC (Table 5).

Non-linear relationship between waist circumference and fat-free mass

A drawback of a simple ratio (i.e. WC:hip or WC:height) is that it cannot consider non-linear or allometric relationships between hip and WC or height and WC respectively (Allison *et al.* 1995). Our new proposed index, however, consists of power terms height^3 divided by WC^3. The denominator WC^3 in the height^3:WC^3 ratio implies that at a given FFM (represented by height^3) with gradually increasing WC the increase in metabolic risk is lower than proportional. This is supported by the finding that small increases in intra-abdominal fat area are associated with larger reductions in insulin sensitivity when small amounts of intra-abdominal fat are present. By contrast, this effect diminishes as intra-abdominal fat accumulates (Cnop *et al.* 2002). Although the relationship between WC and visceral adipose tissue was shown to be linear (Kuk *et al.* 2005) the relationship between visceral adipose tissue and insulin sensitivity was shown to be better described by non-linear than by linear models (Gan *et al.* 2003).

Study limitations

The limitations of our new height^3:WC^3 index may be twofold. First, height^3 reflects FFM (Forbes, 1974). However, anatomically as well as metabolically, FFM is a heterogeneous compartment consisting of internal organs and brain as well as muscle mass or connective tissue (Müller *et al.* 2002). The slope of the correlation between FFM and skeletal muscle mass differs between young and elderly subjects (Bosy-Westphal *et al.* 2003), suggesting, that the relationship

of FFM to metabolic risk may differ with advancing age. There are also sex differences in the decay of muscle mass with age, since men experience a more rapid loss of total body K with age than women (He *et al.* 2003). Second, WC is only an indirect measure of body composition that cannot discriminate between the accumulation of subcutaneous and visceral adipose tissue. However, it has been shown that upper-body non-splanchnic fat is the major contributor to systemic availability of NEFA (Nielsen *et al.* 2004), suggesting that the non-discrimination of visceral and upper-body subcutaneous adipose tissue by WC may be less important.

Our empirical observation of the height^3:WC^3 index is derived from the best fit between FFM, WC and risk factors and therefore any causal interpretation is preliminary and should be done with caution. The validity of the suggested new health index has to be investigated in an independent population. Also a larger sample size will be required to investigate appropriate risk-defined cut-off points in men and women, different ethnicities and for different age groups.

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