Impaired endothelium-dependent vasodilation in overweight and obese adult humans is not limited to muscarinic receptor agonists

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Van Guider GP, Stauffer BL, Greiner JJ, DeSouza CA. Impaired endothelium-dependent vasodilation in overweight and obese adult humans is not limited to muscarinic receptor agonists. Am J Physiol Heart Circ Physiol 294: H1685–H1692, 2008. First published February 15, 2008; doi:10.1152/ajpheart.01281.2007.—Muscarinic receptor agonists have primarily been used to characterize endothelium-dependent vasodilator dysfunction with overweight/obesity. Reliance on a single class of agonist, however, yields limited, and potentially misleading, information regarding endothelial vasodilator capacity. The aims of this study were to determine 1) whether the overweight/obesity-related reduction in endothelium-dependent vasodilation extends beyond muscarinic receptor agonists and 2) whether the contribution of nitric oxide (NO) to endothelium-dependent vasodilation is reduced in overweight/obese adults. Eighty-six middle-aged and older adults were studied: 42 normal-weight (BMI 23.4 ± 0.3 kg/m²) and 44 overweight/obese (BMI 30.3 ± 0.6 kg/m²) subjects. Forearm blood flow (FBF) responses to intra-arterial infusions of acetylcholine in the absence and presence of the endothelial NO synthase inhibitor Nω-monomethyl-L-arginine, methacholine, bradykinin, substance P, isoproterenol, and sodium nitroprusside were measured by strain-gauge plethysmography. FBF responses to each endothelial agonist were significantly blunted in the overweight/obese adults. Total FBF (area under the curve) to acetylcholine (50 ± 5 vs. 79 ± 4 ml/100 ml tissue), methacholine (55 ± 4 vs. 86 ± 5 ml/100 ml tissue), bradykinin (62 ± 5 vs. 85 ± 4 ml/100 ml tissue), substance P (57 ± 4 vs. 57 ± 5 ml/100 ml tissue), and isoproterenol (62 ± 4 vs. 82 ± 6 ml/100 ml tissue) were 30%-40% lower in the overweight/obese than normal-weight adults. Nω-monomethyl-L-arginine significantly reduced the FBF response to acetylcholine to the same extent in both groups. There were no differences between the groups in the FBF responses to sodium nitroprusside. These results indicate that agonist-stimulated endothelium-dependent vasodilation is universally impaired with overweight/obesity. Moreover, this impairment appears to be independent of NO cell surface receptors; intracellular signaling pathways; nitric oxide.
stroke; diabetes (fasting plasma glucose >7.0 mmol/l) (2); dyslipoproteinemia (total cholesterol ≥6.0 mmol/l; triglycerides ≥3.0 mmol/l) (11); or hypertension (blood pressure ≥140/90 mmHg) (7). All subjects were screened for clinical evidence of coronary artery disease with resting and maximal-exercise electrocardiograms and blood pressure. None of the subjects smoked or were taking medication, including vitamins. All the women were ≥1 yr (mean 7 ± 2 yr) postmenopause and had never used hormone replacement therapy or discontinued use of hormone replacement therapy ≥1 yr before the start of the study. The research study and its potential risks and benefits were explained fully before the subjects provided written informed consent according to the guidelines of the University of Colorado at Boulder. This study was approved by the University of Colorado at Boulder Human Research Committee.

**Measurements**

**Body composition.** Body mass was measured to the nearest 0.1 kg with a medical beam balance (Detecto, Webb City, MO). Percent body fat was determined by dual-energy X-ray absorptiometry (Lunar Radiation, Madison, WI). BMI was calculated as weight (kg) divided by height (m) squared. Minimal waist circumference was measured according to previously published guidelines (16).

**Treadmill exercise test.** For assessment of aerobic fitness, subjects performed incremental treadmill exercise using a modified Balke protocol as previously described (10). Maximal oxygen consumption (VO2max) was measured using online computer-assisted open-circuit spirometry.

**Metabolic measurements.** Fasting plasma lipid and lipoprotein, glucose, and insulin concentrations were determined using standard techniques by the clinical laboratory affiliated with the General Clinical Research Center. Insulin resistance was estimated using the homeostasis model assessment derived from fasting glucose and insulin concentrations (18). Plasma concentrations of oxidized low-density lipoprotein (oxLDL), C-reactive protein (CRP), and asymmetric dimethylarginine (ADMA) were determined by enzyme immunoassay (33).

**Intra-arterial infusion protocols.** All measurements were performed in a temperature-controlled room between 7 and 10 AM after a 12-h overnight fast. Under strict aseptic conditions, a 5-cm, 20-gauge catheter was inserted into the brachial artery of the nondominant arm under local anesthesia (1% lidocaine). Forearm blood flow (FFB) was measured in the experimental (nondominant) and the contralateral (dominant) forearm using strain-gauge venous occlusion plethysmography (D. E. Hokanson) as previously described (9). FFB responses are presented in milliliters per 100 milliliters of forearm volume per minute. The total amount of blood flow across the forearm in response to each agonist was calculated as the area under each curve above baseline with use of a trapezoidal model. Before the beginning of the study, permission was obtained from the US Food and Drug Administration to administer methacholine, bradykinin, substance P, and Nω-monomethyl-l-arginine (l-NMMA) to humans.

**Protocol 1.** In 23 of the 42 normal-weight (BMI = 23.3 ± 0.4 kg/m², 10 men and 9 women) and 24 of the 44 overweight/obese (BMI = 30.2 ± 0.9 kg/m², 13 men and 7 women) subjects who did not participate in protocol 1. After acetylcholine was infused at the doses noted above and blood flow was allowed to return to resting levels, l-NMMA was infused at 2.5 mg·100 ml tissue⁻¹·min⁻¹ for 5 min. Immediately thereafter, the acetylcholine dose response was repeated with the continuous infusion of l-NMMA.

**Statistical Analysis**

Differences in subject baseline characteristics and area under the curve data were determined by ANOVA. Group differences in FBF responses to each vasoactive drug were determined by repeated-measures ANOVA. Because there were no significant sex differences with respect to the main effect of overweight/obesity on any of the key outcome variables, the data were pooled and are presented together. Also, because there were no significant differences in the responses to the vasoactive agents between the overweight (BMI = 27–29.9 kg/m²) and obese (BMI ≥ 30 kg/m²) adults, the groups were combined and referred to as overweight/obese. The data were analyzed using JMP 6 statistical software (SAS, Cary, NC). Values are means ± SE. Statistical significance was set a priori at P < 0.05.

**RESULTS**

Table 1 presents selected subject characteristics. By design, body mass, BMI, and waist circumference were higher (P < 0.05 vs. normal weight).

**Table 1. Selected subject characteristics**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Normal Weight (n = 42)</th>
<th>Overweight/Obese (n = 44)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, yr</td>
<td>54±1</td>
<td>54±1</td>
</tr>
<tr>
<td>Sex, M/F</td>
<td>21/21</td>
<td>28/16</td>
</tr>
<tr>
<td>Body mass, kg</td>
<td>69.9±1.7</td>
<td>90.8±2.2*</td>
</tr>
<tr>
<td>Body fat, %</td>
<td>28.3±1.0</td>
<td>36.0±1.2*</td>
</tr>
<tr>
<td>BMI, kg/m²</td>
<td>23.4±0.3</td>
<td>30.3±0.6*</td>
</tr>
<tr>
<td>Waist circumference, cm</td>
<td>81.8±1.4</td>
<td>100.7±2.1*</td>
</tr>
<tr>
<td>BP, mmHg</td>
<td>117±2</td>
<td>122±1*</td>
</tr>
<tr>
<td>Systolic</td>
<td>76±1</td>
<td>78±1</td>
</tr>
<tr>
<td>Diastolic</td>
<td>2.3±0.1</td>
<td>2.5±0.1</td>
</tr>
<tr>
<td>Max O2 uptake, l/min</td>
<td>5.1±0.6</td>
<td>5.2±0.1</td>
</tr>
<tr>
<td>Total cholesterol, mmol/l</td>
<td>3.2±0.6</td>
<td>3.3±0.9</td>
</tr>
<tr>
<td>HDL-C, mmol/l</td>
<td>1.4±0.3</td>
<td>1.2±0.3</td>
</tr>
<tr>
<td>TG, mmol/l</td>
<td>1.1±0.5</td>
<td>1.4±0.7*</td>
</tr>
<tr>
<td>Glucose, mmol/l</td>
<td>4.9±0.5</td>
<td>5.2±0.5*</td>
</tr>
<tr>
<td>Insulin, pmol/l</td>
<td>27.9±2.9</td>
<td>41.7±3.0*</td>
</tr>
<tr>
<td>ADMA, μmol/l</td>
<td>1.0±0.1</td>
<td>1.6±0.1*</td>
</tr>
<tr>
<td>CRP, mg/l</td>
<td>0.9±0.2</td>
<td>3.2±0.5*</td>
</tr>
<tr>
<td>oxLDL, U/l</td>
<td>45.6±1.9</td>
<td>55.9±2.7*</td>
</tr>
</tbody>
</table>

Values are means ± SE. BMI, body mass index; BP, blood pressure; HDL-C, HDL cholesterol; LDL-C, LDL cholesterol; TG, triglycerides; HOME-IR, homeostasis model assessment of insulin resistance; ADMA, asymmetric dimethylarginine; CRP, C-reactive protein; oxLDL, oxidized LDL. *P < 0.05 vs. normal weight.
Acetylcholine. Figure 1 shows the FBF responses to acetylcholine in the normal-weight and overweight/obese groups. The overweight/obese subjects demonstrated a markedly blunted vasodilator response to acetylcholine. The increase in the FBF response to acetylcholine was ~25% less ($P < 0.01$) in the overweight/obese subjects (from $4.3 \pm 0.2$ to $11.4 \text{ ml/100 ml tissue}^{-1}\cdot\text{min}^{-1}$) than normal-weight controls (from $4.5 \pm 0.2$ to $15.4 \text{ ml/100 ml tissue}^{-1}\cdot\text{min}^{-1}$). As a result, total FBF to acetylcholine (area under the FBF curve) was ~40% lower in the overweight/obese subjects than normal-weight controls ($50 \pm 5$ vs. $79 \pm 4$ ml/100 ml tissue).

Methacholine. Methacholine was administered to 22 of the 23 normal-weight controls and 21 of the 24 overweight/obese subjects because of drug availability. Similar to acetylcholine, FBF responses to methacholine were significantly related to differences in adiposity (Fig. 2). The FBF response to methacholine was ~25% lower ($P < 0.01$) in the overweight/obese subjects than normal-weight controls.

Protocol 1: FBF Responses to Acetylcholine, Methacholine, Bradykinin, Substance P, Isoproterenol, and Sodium Nitroprusside

Resting FBF in the noninfused arm and mean arterial pressure remained constant throughout the infusion protocols and were not significantly different between the groups. Blood flow in the infused arm returned to baseline levels after the infusion of each agonist and was not significantly different between the groups.
subjects (from 4.2 ± 0.2 to 12.7 ± 0.6 ml·100 ml tissue⁻¹·min⁻¹) than normal-weight controls (from 4.6 ± 0.2 to 17.3 ± 0.6 ml·100 ml tissue⁻¹·min⁻¹). In addition, total FBF to methacholine was ~30% lower (P < 0.05) in the overweight/obese subjects than normal-weight controls (55 ± 4 vs. 86 ± 5 ml/100 ml tissue).

Bradykinin. FBF responses to bradykinin are shown in Fig. 3. In response to bradykinin stimulation, FBF was ~20% lower (P < 0.01) in the overweight/obese subjects (from 4.1 ± 0.3 to 12.9 ± 0.7 ml·100 ml tissue⁻¹·min⁻¹) than normal-weight controls (from 4.6 ± 0.2 to 16.4 ± 0.6 ml·100 ml tissue⁻¹·min⁻¹). Consequently, total FBF to bradykinin was lower (~25%, P < 0.05) in the overweight/obese subjects than normal-weight controls (62 ± 5 vs. 85 ± 4 ml/100 ml tissue).

Substance P. Figure 4 shows the FBF responses to substance P in the normal-weight and overweight/obese groups. The obese subjects demonstrated significantly reduced vasodilator responses to substance P: the FBF response to substance P was ~25% lower in the overweight/obese subjects (from 4.2 ± 0.2 to 10.6 ± 0.6 ml·100 ml tissue⁻¹·min⁻¹) than normal-weight controls (from 4.6 ± 0.2 to 13.4 ± 0.8 ml·100 ml tissue⁻¹·min⁻¹). Consequently, total FBF to substance P was ~35% less in the overweight/obese subjects than normal-weight controls (37 ± 4 vs. 57 ± 5 ml/100 ml tissue).

Isoproterenol. Similar to acetylcholine, methacholine, bradykinin, and Substance P, forearm vascular responses to isoproterenol were diminished in the overweight/obese subjects (Fig. 5). The increase in the FBF response to isoproterenol was ~25% lower (P < 0.01) in the obese subjects (from 4.4 ± 0.2 to 13.8 ± 0.8 ml·100 ml tissue⁻¹·min⁻¹) than normal-weight controls (from 4.7 ± 0.2 to 16.9 ± 0.8 ml·100 ml tissue⁻¹·min⁻¹). Total FBF to isoproterenol was significantly (~25%) less in the overweight/obese subjects than normal-weight controls (62 ± 4 vs. 82 ± 6 ml/100 ml tissue).

Fig. 3. FBF responses (A) and total FBF (area under the curve; B) to bradykinin in normal-weight and overweight/obese groups. Values are means ± SE. *P < 0.05 vs. normal weight.

Fig. 4. FBF responses (A) and total FBF (area under the curve; B) to substance P in normal-weight and overweight/obese groups. Values are means ± SE. *P < 0.05 vs. normal weight.
Sodium nitroprusside. There were no significant differences between the groups in the FBF responses to sodium nitroprusside (Fig. 6).

Protocol 2: Effects of L-NMMA on FBF Responses to Acetylcholine

Consistent with our findings in protocol 1, FBF responses to acetylcholine were significantly lower in the overweight/obese subjects (from 4.3 ± 0.2 to 11.1 ± 0.7 ml·100 ml tissue⁻¹·min⁻¹) than normal-weight controls (from 4.6 ± 0.3 to 14.2 ± 0.9 ml·100 ml tissue⁻¹·min⁻¹). L-NMMA produced similar reductions (~30%) in FBF at baseline in the overweight/obese subjects (from 4.2 ± 0.2 to 2.6 ± 0.2 ml·100 ml tissue⁻¹·min⁻¹) and normal-weight controls (from 4.3 ± 0.2 to 2.7 ± 0.2 ml·100 ml tissue⁻¹·min⁻¹). Infusion of L-NMMA significantly blunted the acetylcholine-mediated vasodilator response in both groups (Fig. 7). The magnitude of the reduction (~20%) in FBF was not significantly different between the overweight/obese subjects and normal-weight controls.

DISCUSSION

It is well established that the forearm vasodilator response to acetylcholine and methacholine is significantly impaired in overweight and obese adult humans (23, 30, 31). The results of the present study confirm and extend these findings, inasmuch as we demonstrate for the first time that FBF responses to other endothelial agonists are also significantly impaired with increased adiposity. Indeed, in addition to acetylcholine and methacholine, forearm vasodilation to bradykinin, substance P, and isoproterenol was substantially lower (~30%) in overweight/obese adults than their normal-weight peers. Moreover, the results of the present study suggest that impaired endothelium-dependent vasodilation with increased adiposity is not due to diminished NO production.
To comprehensively assess the influence of overweight/obesity on endothelium-dependent vasodilation in conscious humans, we determined the FBF responses to a variety of endothelial agonists that act via different endothelial cell surface receptors, intracellular membrane-bound G proteins, and signal transduction pathways (27). Acetylcholine and methacholine are muscarinic receptor agonists that stimulate the phospholipase C-phosphatidylinositol-Ca²⁺/H₁₁₀₀₁ signaling pathway, via the intracellular membrane-bound pertussis toxin-sensitive G protein, leading to increased intracellular Ca²⁺ and the activation of eNOS and, in turn, production and subsequent release of NO (4, 27). Similar to acetylcholine and methacholine, bradykinin stimulates the phospholipase C-phosphatidylinositol-Ca²⁺ intracellular signal transduction pathway; however, this is mediated through B₂-kininergic receptors coupled to a pertussis toxin-insensitive G protein (3). Substance P and acetylcholine share the same G protein signaling pathway, but substance P interacts with tachykinin receptors on the endothelial cell surface (26). Inasmuch as acetylcholine, methacholine, substance P, and bradykinin share the same phospholipase C-phosphatidylinositol-Ca²⁺ intracellular signal transduction pathway, it is possible that impaired Ca²⁺ release may contribute to the impaired responses. However, isoproterenol is a β-adrenoceptor agonist that stimulates vasorelaxation, in part, by activating the adenyllyl cyclase pathway, resulting in cAMP activation of eNOS (5). Thus, in the present study, regardless of the agonist administered, endothelium-dependent vasodilation was significantly reduced in the overweight/obese subjects compared with normal-weight controls. Moreover, the magnitude of impairment in vasodilation was similar among the agonists, suggesting a general endothelial vasomotor abnormality, rather than a specific endothelial receptor or signal transduction pathway defect. Consistent with this postulate, we recently reported that obesity-related impairment in acetylcholine-mediated vasodilation with overweight/obesity is not due to reduced muscarinic receptor responsiveness or sensitivity (32).

The mechanisms responsible for this general dysfunction in agonist-mediated endothelium-dependent vasodilation in overweight/obese adults are not clear. All the endothelial agonists used in the present study stimulate vasodilation, at least in part, by the activation of eNOS and subsequent production of NO. Overweight and obesity are conditions characterized by increased oxidative stress and inflammatory burden (12, 15). Increased oxidative stress and systemic inflammation have been shown to have unfavorable effects on stimulated endothelial NO bioavailability (37). Consistent with previous work (12, 15), our overweight/obese subjects demonstrated higher circulating plasma concentrations of oxLDL and CRP, specific markers of oxidative and inflammatory stress, respectively. Thus a reduction in NO bioavailability would be a logical mechanism underlying the global impairment in vasodilator capacity in the overweight/obese subjects. However, the results of the present study do not support this postulate. In response to infusion of acetylcholine + L-NMMA, we observed almost identical reductions in forearm vasodilation in the normal-weight controls and overweight/obese subjects, suggesting that the contribution of NO to acetylcholine-mediated vasodilation is preserved with increased adiposity. In addition, we observed no differences in circulating levels of the endogenous eNOS inhibitor ADMA or resting FBF responses to L-NMMA between the overweight/obese subjects and normal-weight controls. Consistent with our findings, Nielsen et al. (22) reported...
similar FBF responses to L-NMMA in a comparison of young normal-weight and upper body-obese men. Complementing these findings, a recent in vitro study involving endothelial cells isolated from normal-weight and overweight/obese adults revealed no group differences in eNOS protein expression (28). Thus, taken together, these data suggest that adiposity-related endothelial vasodilator dysfunction is not due to impaired eNOS activity or NO production.

It is possible that elevated vasoconstrictor tone may blunt endothelial vasodilator capacity in overweight/obese adults. For example, endothelin-1 (ET-1)-mediated vasoconstriction has been reported to be elevated in overweight/obese adults. ET-1, which is produced primarily by vascular endothelial cells, is one of the most potent endogenous vasoconstrictor peptides (36). Mather et al. (17) showed that ET-1-mediated vasoconstrictor tone is higher in overweight/obese than normal-weight adults and that this increase in vasoconstrictor activity contributes to the endothelial vasodilator dysfunction associated with increased body fatness. Specifically, they demonstrated that blockade of the ETA receptor restored leg blood flow responses to methacholine in overweight and obese adults to levels similar to that of normal-weight controls. In addition, angiotensin II-stimulated forearm vasoconstriction has been reported to be higher in obese men (22). Thus an increase in endothelial vasoconstrictor tone resulting in limited vasodilator capacity is a tenable hypothesis to account for the general impairment in endothelium-dependent vasodilation in the overweight/obese adults.

From a clinical perspective, it is important to emphasize that there were no significant differences in the FBF responses to any of the endothelial agonists (or sodium nitroprusside) between the overweight (mean BMI = 27.7 ± 0.3 kg/m²) and obese (BMI = 33.4 ± 0.8 kg/m²) subjects within the overweight/obese group. Indeed, the peak FBF response to acetylcholine (12.3 ± 0.7 vs. 10.4 ± 1.0 μg·100 ml tissue⁻¹·min⁻¹), methacholine (12.3 ± 0.8 vs. 12.9 ± 0.8 μg·100 ml tissue⁻¹·min⁻¹), bradykinin (13.2 ± 0.5 vs. 11.7 ± 1.0 μg·100 ml tissue⁻¹·min⁻¹), substance P (11.3 ± 0.9 vs. 9.9 ± 0.8 μg/100 ml tissue), and isoproterenol (14.3 ± 1.0 vs. 13.1 ± 1.0 μg/100 ml tissue) was similar between the groups, irrespective of the marked difference in BMI. These data indicate that the impaired endothelial vasodilator function commonly observed with obesity is apparent in the overweight state. This finding complements a previous study from our laboratory (34), in a comparable study population, demonstrating similar levels of endothelial fibrinolytic dysfunction in overweight and obese subjects compared with normal-weight adults. Thus increased adiposity resulting in an overweight or obese body status classification is associated with unfavorable changes in vascular endothelial function. Inasmuch as ~65% of the US population is overweight (13) and endothelial vasoconstriction and fibrinolytic dysfunction are key antecedents to cardiovascular disease and acute vascular events (19, 21, 25, 29), it is imperative that interventions aimed at reducing adiposity and improving endothelial function not only target obese adults but also those who are mild to moderately overweight.

Three experimental considerations regarding this study should be mentioned. 1) Considering our cross-sectional study design, we cannot dismiss the possibility that genetic and/or lifestyle behaviors may have influenced the results of our group comparisons. To minimize the influence of lifestyle behaviors, all subjects were nonsmokers, were not currently taking medication that could influence endothelium-dependent vasodilation, and did not differ in habitual physical activity. In addition, we studied carefully screened normal-weight and overweight/obese adults to eliminate the confounding effects of clinically overt cardiovascular and metabolic disease. 2) Although we determined the influence of overweight/obesity on forearm endothelium-dependent vasodilation responses to a number of agonists, the role of NO in the vasodilator responses was only assessed using L-NMMA with acetylcholine. Inasmuch as the contribution of NO to endothelium-mediated vasodilation can vary substantially depending on the agonist used, we cannot confidently infer from our results similar findings among the other agents. For example, up to 70% of the forearm vasodilation induced by substance P has been shown to be NO mediated, compared with 30–40% for acetylcholine (5, 8, 20). It is possible that overweight/obesity-related differences in NO-mediated vasodilation may emerge with agonists that are predominantly NO dependent, such as substance P. 3) The results of the present study pertain only to the forearm vasculature. Although acetylcholine- and methacholine-mediated endothelium-dependent vasodilation has been shown to be impaired in the coronary and femoral arteries of overweight/obese adults (1, 31), it is unknown whether the extent of dysfunction observed in the forearm in response to various agonists is similar to that in other vascular beds.

In conclusion, the results of the present study demonstrate that increased adiposity is associated with profound impairment in endothelium-dependent vasodilation that extends beyond muscarinic receptor agonists. Regardless of the endothelial agonist employed, forearm vasodilator capacity is markedly lower in overweight/obese than normal-weight adults. Moreover, the impairment in endothelial vasodilation with overweight/obesity appears to be independent of NO bioavailability. Clinically, it is important to emphasize that the degree of endothelial vasodilator dysfunction observed with obesity is evident in the overweight state, suggesting that any excess adiposity is associated with impaired endothelial vasodilator function.

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GRANTS

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