Endothelial dysfunction involves the systemic expression of an abnormal prothrombotic, proinflammatory vascular phenotype that predicts increased cardiovascular risk. Early studies demonstrating the existence of endothelial dysfunction and its relationship to cardiovascular risk factors and atherosclerosis were performed directly in the coronary circulation. However, given the risk and expense of these studies and the systemic nature of endothelial dysfunction, noninvasive methods for measurement endothelial function emerged, including flow-mediated dilation (FMD) of the brachial artery and digital pulse arterial tonometry (PAT). Important correlations of FMD and PAT with cardiovascular risk factors, coronary endothelial dysfunction, and future cardiovascular risk have buoyed the use of these methodologies in cardiovascular research.

While convenient, noninvasive methods such as FMD and PAT employed to follow the effects of disease states and interventions do not allow for significant mechanistic insights into how diseases and interventions alter endothelial function. Circulating markers provide some insights but these surrogates do not necessarily reflect activity at the tissue level. Subcutaneous adipose arterioles are easily accessible through minimally invasive means. Recent data suggest, similarly to FMD and PAT, acetylcholine-induced vasodilation of subcutaneous arterioles may depend on nitric oxide (NO) production from endothelium-derived NO synthase. However, data regarding the relative contributions of traditional cardiovascular risk factors to endothelium-dependent vasodilation in subcutaneous arterioles is lacking. Furthermore, data designed to determine associations between endothelial function in human subcutaneous arterioles and noninvasive risk factors, coronary endothelial dysfunction, and future cardiovascular risk have buoyed the use of these methodologies in cardiovascular research.

Noninvasive measurements of endothelial function predict future adverse cardiovascular events, but offer limited opportunities for mechanistic insights into phenotypic observations. Subcutaneous adipose arterioles, accessible through minimally invasive methods, provide an opportunity for complimentary mechanistic studies. Limited data relating subcutaneous arteriolar endothelial function, cardiovascular risk factors, and noninvasive measurements of endothelial function currently exist.

Forty-four subjects underwent noninvasive studies of endothelial function (brachial reactivity (flow-mediated dilation (FMD) and digital pulse arterial tonometry (PAT)) and measurements of endothelial-dependent vasodilation of gluteal subcutaneous arterioles to acetylcholine. Arteriolar endothelial function was measured (i) percent vasodilation to maximal acetylcholine dose \((10^{-7}\ \text{mol/l})\) and (ii) total area under the curve (AUC) for the entire acetylcholine dose–response curve (total AUC-acetylcholine (Ach), doses \(10^{-10}–10^{-5}\ \text{mol/l}\)).

Acetylcholine responses were almost completely nitric oxide (NO) dependent. Total AUC-Ach predicted FMD and PAT, but maximal acetylcholine vasodilation was not associated with these measures. A history of hypertension, diabetes, smoking, and low-density lipoprotein cholesterol levels were independent predictors of total AUC-Ach. In regression models, total AUC independently predicted FMD.

Acetylcholine vasodilator responses in human gluteal subcutaneous arterioles are NO synthase dependent and correlate with cardiac risk factors and in vivo measures of endothelial function. These data suggest subcutaneous arterioles offer an opportunity for translational studies of mechanisms of modulating NO bioavailability relevant to in vivo endothelial function measures.

**Keywords:** arterioles; blood pressure; cardiovascular risk; endothelial function; flow-mediated dilation; hypertension; nitric oxide
measures of endothelial function are limited. Data linking endothelial function in these vascular beds would suggest studies of subcutaneous arterioles in conjunction with FMD and PAT measurements could provide mechanistic insights into phenotypical alterations in FMD and PAT. We hypothesized that acetylcholine-induced endothelium-dependent vasodilation of gluteal subcutaneous arterioles would correlate with traditional cardiovascular risk factors and both FMD and PAT in humans with a range of cardiovascular risk profiles.

METHODS

Study population. Subjects undergoing PAT and/or FMD with concomitant subcutaneous arteriolar vasodilation data from cross-sectional studies of endothelial function performed at the Medical College of Wisconsin from 2007 to 2011 were included in the study population (data not published to date). Criteria for qualifying as having hypertension, diabetes, and/or hypercholesterolemia are described in the Supplementary Methods online. Subjects with a history of coronary artery disease, peripheral vascular disease, cerebrovascular disease, or chronic renal or liver disease were excluded. All study protocols were approved by institutional review board of the Medical College of Wisconsin and informed consent was obtained from all participants prior to any study procedures.

Study protocol. All studies were performed in the Adult Translation Research Unit at the Medical College of Wisconsin from 7 to 10 AM. All subjects fasted for at least 6 h prior to their study visits. Current smokers refrained from smoking for 24 h prior to their study visits. A medical history as well as subject height, weight, and waist circumference were measured and recorded. Blood pressure and heart rate measurements were made in triplicate and averaged for a final result. Prior to in vivo endothelial function tests, subjects laid in a supine position in a quiet, dimly lit, temperature controlled (22–24°C) room for 20 min.

Measurements of in vivo endothelial function. Brachial artery images were captured prior to and following blood pressure cuff inflation and analyzed as previously described to determine the extent of resting and post-hyperemic shear and FMD in the brachial artery. FMD was recorded both as the absolute change in brachial diameter (FMDmm) and the percent change in diameter (FMD%). In a subset of 40 subjects, measurement of endothelium-independent vasodilation (NMD%) was performed following administration of 0.4 mg of sublingual nitroglycerin as previously described.

Digital PAT measurements were performed concomitantly with FMD measurements using EndoPAT 2000 (Itamar Medical, Caesarea, Israel). EndoPAT results were recorded and are reported using the methodology suggested by the Framingham study as most strongly correlated with cardiovascular risk factors. Greater methodological details are found in the Supplementary Methods online.

Gluteal adipose biopsy and measurement of arteriolar endothelial function. Subcutaneous arterioles were obtained by gluteal adipose biopsy under local anesthesia (1% lidocaine) using sterile technique. A small (~1–1.5 cm) horizontal incision was made in the upper external gluteal quadrant and gluteal subcutaneous adipose tissue was taken from the point located superior to gluteus maximus muscle ~3–5 cm cephalad of the greater trochanter. Adipose tissue (~1.5 × 1.0 × 1.0 cm^3 in size) was removed by sharp dissection. The incision was closed with an absorbable suture and Steristrips. The fat sample was transferred immediately into cold HEPES buffer (4°C) and taken for immediate analysis. Endothelium-dependent vasodilation of adipose arterioles dissected from these samples under light microscopy was measured by video microscopy previously described. Greater methodological detail can be found in the Supplementary Methods online. Our overall success rate in obtaining arterioles suitable and viable for study is ~75%.

Vasodilation was recorded as a percentage change from baseline diameter measured following endothelin-1 preconstriction (at least 50% constriction with endothelin-1 was used as a marker of vessel viability). We plotted the percent vasodilation at each dose of acetylcholine from 10^{-10} to 10^{-5} mol/l and calculated the area under the entire dose–response curve (total AUC-acetylcholine (Ach)) for each arteriole. Endothelium-independent dilation determined at the end of each experiment with papaverine (0.2 mmol/l). Following washout, re-equilibration and repeat preconstriction, a subset of 16 vessels were incubated with 100 μmol/l L-NAME, NO synthase inhibitor) and exposed to increasing doses of Ach from 10^{-10} to 10^{-5} mol/l to determine the contribution of NO synthase to vasodilation of these arterioles.

Statistical analysis. The statistical analysis was done using SPSS 19.0 (SPSS, Chicago, IL) and SigmaStat 12.0. Full details on the statistical analyses can be found in the Supplementary Methods online. P values of <0.05 were considered statistically significant.

RESULTS

Participants

From our studies, 47 subjects had adipose tissue arterioles available for vasoreactivity experiments. Three subjects from this group were excluded as they did not have FMD or PAT data for analysis. Forty-four patients had both FMD measurements as well as arteriolar vasoreactivity data, while PAT measures were obtained in 34 subjects in this group. The baseline characteristics of the all 44 subjects are listed in Table 1. In the healthy subject group, there was 1 subject who reported diet-controlled high cholesterol and 2 current smokers. Systolic blood pressure and heart rate were significantly lower in the healthy group, and there was a strong trend toward a lower body mass index in healthy group. There were no significant differences in these demographic variables between individuals who underwent both FMD and PAT versus those who...
who underwent FMD alone (data not shown). A total of eight subjects (18%) were on concomitant HMG CoA reductase therapy, all in the group of subjects with type 2 diabetes and/or hypertension. HMG CoA reductase therapy was the only form of lipid-lowering therapy in this study population.

**Measurements of in vivo endothelial function and endothelial function in 1st order arterioles and mechanism of acetylcholine-induced vasodilation in subcutaneous arterioles**

Our findings are summarized in Table 2. As expected, both in vivo (FMD%, FMDmm) and in vitro endothelial function were impaired in patients with diabetes and/or hypertension compared to healthy subjects. We observed a trend toward decreased PAT in patients with diabetes and/or hypertension which did not reach statistical significance in this study. Neither FMD% nor FMDmm correlated with patients with diabetes and/or hypertension (r = 0.06 and 0.28, P = 0.97 and 0.88 for FMD% and FMDmm, respectively). There were no differences between groups with respect to the concentration of endothelin-1 required for vessel preconstriction prior to acetylcholine injection. Total AUC-Ach was significantly associated with FMD%, FMDmm, and PAT, but not with peak hyperemic shear or NMD% (Figure 2). We found no associations between maximal acetylcholine vasodilation and FMD% (r = 0.24, P = 0.12), FMDmm (r = 0.25, P = 0.11), PAT (r = 0.18, P = 0.34), peak hyperemic shear (r = 0.05, P = 0.73), or NMD% (r = 0.22, P = 0.18). There were no associations between any measurement of arteriolar endothelial function and resting brachial diameter (p = 0.04, P = 0.79 and r = 0.003, P = 0.99 for total AUC-Ach).

**Strengths of associations between measures of in vivo endothelial function and measurements of endothelial function in subcutaneous arterioles**

Given the >95% NO synthase dependence of arteriolar vasodilation in both subjects with and with diabetes and/or hypertension (Figure 1), all subjects were grouped together for analyses of associations to in vivo measurements of endothelial function. Total AUC-Ach was significantly associated with FMD%, FMDmm, and PAT, but not with peak hyperemic shear or NMD% (Figure 2). We found no associations between maximal acetylcholine vasodilation and FMD% (r = 0.24, P = 0.12), FMDmm (r = 0.25, P = 0.11), PAT (r = 0.18, P = 0.34), peak hyperemic shear (r = 0.05, P = 0.73), or NMD% (r = 0.22, P = 0.18). There were no associations between any measurement of arteriolar endothelial function and resting brachial diameter (p = 0.04, P = 0.79 and r = 0.003, P = 0.99 for total AUC-Ach).

Illustration of the vasodilatory response to acetylcholine in the absence and presence of 100 µmol/l L-NAME is depicted in Figure 1. L-NAME reduced the vasodilator response to acetylcholine in these vessels by ~95% in both subjects with and without diabetes and/or hypertension (P < 0.001 overall for healthy subjects vs. subjects with diabetes and/or hypertension in the absence of L-NAME). All vessels dilated over 95% to 0.2 mmol/l papaverine, with no significant differences between healthy and diabetes and/or hypertension study groups (data not shown).
Subcutaneous Arterioles and Endothelial Function

emerged as an independent predictor of both FMDmm (model $R^2 = 0.17, \beta = 0.31 (P = 0.006)$) and FMD% (model $R^2 = 0.15, \beta = 0.39 (P = 0.01)$). The model for PAT was not significant (model $R^2 = 0.40, P = 0.06$).

**Associations of total AUC-Ach with cardiovascular risk factors**

Overall, we found total AUC-Ach was inversely associated with the presence of diabetes mellitus, a history of hypertension, a history of high cholesterol, and current lipid-lowering therapy (Table 3). Body mass index and heart rate trended toward inverse correlations with total AUC-Ach. In a stepwise multivariable model including all of these variables except lipid-lowering therapy (likely a marker for a history of high cholesterol rather than a biological effect), only histories of diabetes and hypertension remained significant predictors.

**DISCUSSION**

This study reports several novel findings. First, in subjects with a wide range of cardiovascular risk, endothelium-dependent vasodilation to acetylcholine in intact gluteal subcutaneous arterioles is associated traditional cardiovascular risk factors, including hypertension, diabetes, and hypercholesterolemia. Second, in humans without established coronary artery disease, our data establish the NOS dependence of the acetylcholine-induced vasodilation in human gluteal subcutaneous arterioles. Third, in subcutaneous gluteal arterioles, the ex-vivo endothelial-dependent response to acetylcholine is positively associated with common in vivo measurements endothelial function, FMD, and PAT. These data suggest ex-vivo measurements of...
Our data extended these findings by demonstrating measurements of subcutaneous arterioles measured by pressurized myography and FMD% was shown in 16 patients with hypertension. The strength of this correlation was significantly attenuated by exclusion of 4 subjects with significantly impaired FMD%. In a second study of 33 subjects, 25 with established coronary artery disease, FMD% significantly correlated with peak flow-induced dilation of abdominal fat pad subcutaneous arterioles measured by pressurized myography ($r = 0.46$, $P < 0.01$). However, the acetylcholine vasodilatory response in vessels from patients with coronary artery disease was paradoxically significantly more robust than that in healthy controls. We found associations between FMD and PAT and acetylcholine-induced vasodilation over the full range of acetylcholine doses, but no correlation between either in vivo measurement or peak response to acetylcholine. Differences between prior work and our results may relate to differences in vessel size (on average $\frac{1}{2}$ the luminal diameter compared to both prior studies), technique for measuring vasodilation (pressurized video microscopy vs. myography), the source of fat, or potentially a shift in the balance of paracrine factors (e.g., EDHF, prostaglandins, NO, and hydrogen peroxide) responsible for endothelium-dependent vasodilation in patients with established coronary artery disease.

Our data also significantly extend previously reported findings by showing the association between acetylcholine-induced arteriolar vasodilation and in vivo measures of endothelial function in a population comprised of $\geq 50\%$ healthy subjects. We found that increased NO production is the primary mechanism acetylcholine-induced vasodilation in subcutaneous gluteal arterioles in our study population. Taken together with the established mechanistic links between PAT, FMD, and NO bioavailability, we believe the association seen between PAT, FMD, and subcutaneous arteriolar vasodilation most likely relates to similar alterations in endothelial NO synthase-dependent NO bioavailability. Our hypothesis is supported by prior data demonstrating reduced NO bioavailability in subcutaneous vessels of patients with hypertension or type 2 diabetes in parallel with in vivo data from separate studies showing consistent impairment in brachial FMD and PAT in the setting of either risk factor. Interestingly, the relatively modest correlations we report here between FMD and acetylcholine-induced vasodilation of gluteal adipose arterioles may relate to emerging data suggesting FMD in certain populations may not be as reliant on NO production as previously suspected. Future studies comparing NO production in subcutaneous arterioles and the NO dependent portions of the FMD and PAT responses in humans are necessary.

Our data showed negative univariate correlation between total AUC-Ach and lipid-lowering therapy. This finding most likely relates to confounding by indication rather than a true association. Individuals on HMG CoA reductase therapy had significantly lower lipid-lowering therapy levels than those not on these medications ($82 \pm 9$ mg/dl vs. $102 \pm 4$ mg/dl, $P = 0.045$) and univariate analysis revealed a known history of high cholesterol correlated negatively with total AUC-Ach.

Our data have several limitations. First, pharmacological exposures can influence measurements acetylcholine-induced

### Table 3 | Univariable and multivariable predictors of total acetylcholine-induced arteriolar vasodilation AUC($10^{-10}$-$10^{-5}$ mol/l)

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Univariate</th>
<th>Multivariate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\rho$</td>
<td>$P$ value</td>
</tr>
<tr>
<td>Age</td>
<td>$-0.07$</td>
<td>$0.64$</td>
</tr>
<tr>
<td>Sex (F = 0, M = 1)</td>
<td>$-0.08$</td>
<td>$0.63$</td>
</tr>
<tr>
<td>History of diabetes mellitus</td>
<td>$-0.60$</td>
<td>$&lt;0.001$</td>
</tr>
<tr>
<td>History of hypertension</td>
<td>$-0.42$</td>
<td>$0.004$</td>
</tr>
<tr>
<td>History of high cholesterol</td>
<td>$-0.52$</td>
<td>$&lt;0.001$</td>
</tr>
<tr>
<td>Smoking status (1 = current/past, 0 = never)</td>
<td>$0.09$</td>
<td>$0.57$</td>
</tr>
<tr>
<td>Family history of CAD</td>
<td>$-0.16$</td>
<td>$0.31$</td>
</tr>
<tr>
<td>Body mass index</td>
<td>$-0.29$</td>
<td>$0.06$</td>
</tr>
<tr>
<td>HDL (≤40 mg/dl)</td>
<td>$-0.06$</td>
<td>$0.70$</td>
</tr>
<tr>
<td>LDL (≥130 mg/dl)</td>
<td>$0.18$</td>
<td>$0.24$</td>
</tr>
<tr>
<td>Triglycerides (≥150 mg/dl)</td>
<td>$-0.25$</td>
<td>$0.10$</td>
</tr>
<tr>
<td>Total cholesterol (≥200 mg/dl)</td>
<td>$0.04$</td>
<td>$0.79$</td>
</tr>
<tr>
<td>Lipid-lowering therapy</td>
<td>$-0.41$</td>
<td>$0.006$</td>
</tr>
<tr>
<td>Heart rate</td>
<td>$-0.27$</td>
<td>$0.09$</td>
</tr>
</tbody>
</table>

AUC, area under the curve; CAD, coronary artery disease; HDL, high-density lipoprotein; LDL, low-density lipoprotein.

Values in italics are statistically significant in the multivariable model.

*Model R² = 0.46. Multivariable model includes history of diabetes mellitus, history of hypertension, history of high cholesterol, body mass index, and heart rate.
vasodilation in subcutaneous arterioles. However, we would expect these changes to occur in parallel in the arterioles and in vivo measurements making medications an unlikely cause of significant variation. Second, the correlations we found were relatively modest (ranging between 0.34 and 0.44). However, the correlation sizes are similar in magnitude to studies showing parallel impairments in coronary circulation with FMD (r = 0.36) and PAT (r = 0.41). These moderate size of these correlations are reasonable given the variability of in vivo endothelial function measurements. While we did not find any correlation between either baseline and peak hyperemic shear and acetylcholine-induced vasodilation, we cannot exclude an association between arteriolar vasodilation and other measurements of shear such as shear AUC. Finally, the association between FMD and acetylcholine-induced vasodilation of gluteal arterioles cannot be easily extrapolated to FMD of other conduit vessels. Balanced against these limitations is the novelty of our findings related to the association of endothelial function in subcutaneous vessels to traditional cardiovascular risk factors and associations of measurements of noninvasive in vivo endothelial function in individuals without established coronary artery disease. Furthermore, we identified the likely mechanism of endothelial dependent vasodilation in gluteal subcutaneous arterioles.

In the absence of coronary artery disease, endothelium-dependent vasodilation to acetylcholine in human gluteal subcutaneous arterioles is (i) associated with common cardiovascular risk factors (ii) primarily dependent of endothelial NO synthase activity, and (iii) associated with concomitant measurements of in vivo endothelial function. These data support the concept of endothelial dysfunction as a systemic illness. Associations between endothelial NO synthase-dependent vasodilation of arterioles with FMD and PAT suggest subcutaneous arterioles offer an opportunity for translational studies of mechanisms of modulating NO bioavailability relevant to in vivo measures endothelial function.

Supplementary material is linked to the online version of the paper at http://www.nature.com/ajh

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