Relationships between circulating metabolic intermediates and insulin action in overweight to obese, inactive men and women

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**Objective:** To determine if circulating metabolic intermediates are related to insulin resistance and beta-cell dysfunction in persons at risk for type 2 diabetes.

**Methods:** In 73 sedentary, overweight to obese, dyslipidemic individuals, insulin action was derived from a frequently sampled intravenous glucose tolerance test. Plasma concentrations of 75 amino acids, acylcarnitines, free fatty acids and conventional metabolites were measured with a targeted, mass-spectrometry-based platform. Principal components analysis followed by backward stepwise linear regression was used to explore relationships between measures of insulin action and metabolic intermediates.

**Results:** The 75 metabolic intermediates clustered into 19 factors comprised of biologically related intermediates. A factor containing large neutral amino acids was inversely related to insulin sensitivity ($S_I; R^2=0.26$). A factor containing fatty acids was inversely related to the acute insulin response to glucose ($R^2=0.12$). Both of these factors, age, and a factor containing medium-chain acylcarnitines and glucose were inversely and independently related to the disposition index (DI; $R^2=0.39$). Gender differences were found for metabolic predictors of $S_I$ and DI.

**Conclusions:** In addition to well-recognized risks for insulin resistance, elevated concentrations of large, neutral amino acids independently associated with insulin resistance. Fatty acids were inversely related to pancreatic response to glucose. Both large neutral amino acids and fatty acids were related to an appropriate pancreatic response, suggesting that these metabolic intermediates might play a role in the progression to type 2 diabetes, one by contributing to insulin resistance and the other to pancreatic failure. These intermediates might exert gender-specific effects on insulin action.
With developed countries becoming increasingly less active and more obese, the incidence of type 2 diabetes is growing at an alarming rate. Given the critical role of skeletal muscle in glucose disposal, much work has focused on understanding skeletal muscle insulin resistance. Additionally, because progression to overt type 2 diabetes requires defective pancreatic beta cell secretion of insulin (1), efforts are also underway to dissect mechanisms of pancreatic beta cell failure. Prevailing theories for insulin resistance focus on lipid-mediated mechanisms, but also include insulin resistance mediated by elevated concentrations of amino acids and inflammatory signaling molecules as well as combinations of these (2). Similarly, beta cell dysfunction leading to type 2 diabetes has been linked to cellular stress responses triggered by over-stimulation of insulin synthesis and secretion, as well as effects of lipid mediators to cause changes in key metabolic activities of beta-cells that impair control of insulin secretion (2).

Most of these hypotheses have revolved around elegant physiologic investigations often performed in animal models. However, while these physiologic investigations provide great insight into mechanisms, they do not conclusively illustrate that such mechanisms function at the population level in humans. Using a well-characterized sample from a clinical trial, our objective was to determine if the measurement of metabolic intermediates with a targeted, mass-spectrometry-based platform might provide insight into the pathogenesis of insulin resistance, a harbinger and essential component of type 2 diabetes. Our hypothesis was that in this group of men and women at risk for, but without overt, type 2 diabetes, lipid mediators would be related to insulin resistance and hyperglycemia would be related to beta-cell dysfunction.

**RESEARCH DESIGN AND METHODS**

**Design and Subjects:** This was a cross-sectional evaluation of the relationship between concentrations of circulating metabolic intermediates and insulin action in 73 subjects who enrolled in the first and second Studies of Targeted Risk Reduction Interventions through Defined Exercise (STRRIDE). Inclusion criteria were age between 18 and 70 years, inactivity (not participating in regular exercise), being overweight to mildly obese (body mass index 25-35 kg/m²), dyslipidemia (LDL-cholesterol of 130-190 mg/dl or HDL-cholesterol < 40 mg/dl for men and < 45 mg/dl for women), and post-menopausal status for women. Exclusion criteria included diagnosed diabetes mellitus or fasting glucose > 126 mg/dl, medications known to affect carbohydrate or lipid metabolism, dietary regimen designed to induce weight loss, hypertension (BP > 160/90 mmHg), known cardiovascular disease, tobacco use, and musculoskeletal conditions prohibiting exercise training (3).

**Circulating Metabolite Measurements:** Fasting EDTA plasma was collected from each participant and stored at -80°C. Circulating metabolites were measured in plasma from 73 subjects at study enrollment. Fifteen amino acids, forty-five acylcarnitines, and nine free fatty acids were measured using a targeted, mass-spectrometry-based platform as previously described (4; 5). Briefly, amino acids and acylcarnitines were methanol precipitated, esterified, and analyzed with tandem mass spectrometry (MS/MS). After methylation with iodomethane and partial purification, free fatty acids were measured with gas chromatography/mass spectrometry (GC/MS). Conventional metabolites including glucose, lactate, uric acid, total ketones, β-hydroxybutyrate, and nonesterified free fatty acids were measured with colorimetric
enzymatic assays using a Hitachi 911 analyzer(4). Reagents for Hitachi analyses were obtained from Roche (Indianapolis, IN; glucose, lactate, uric acid) and Wako USA (Richmond, VA; total ketones, β-hydroxybutyrate, nonesterified free fatty acids).

**Metabolic and Cardiovascular Risk Factor Assessments:** A frequently sampled intravenous glucose tolerance test was performed in all subjects. Fasting insulin (Access Immunoassay System, Beckman Coulter, Fullerton, CA) and fasting glucose (YSI model 2300 Stat Plus, Yellow Springs Instruments, Yellow Springs, OH) were measured. Using these concentrations, insulin sensitivity (SI) and the acute insulin response (AIRg) were derived based on Bergman’s Minimal Model (3; 6). The disposition index (DI) was calculated as the mathematical product of insulin sensitivity index and AIRg (SI * AIRg).

**Data analysis:** Our main objective was to determine if metabolic intermediates might be predictive of baseline insulin sensitivity and insulin action. Given the large number of predictors relative to the sample size and collinearity of analytes, principal components analysis (PCA) was employed as a means to reduce the complexity of the variables. Each of the metabolic intermediates was logarithmically transformed [log10 (metabolite + 1)] to approximate a normal distribution. An orthogonal varimax rotation was employed, and factors with an eigenvalue greater than 1 were retained. Individual metabolites with a factor load of >|0.4| for a given PCA-derived factor are reported as composing that factor. Given the presence of certain acylcarnitines having values below the lower limits of quantification (LOQ), sensitivity analyses of PCA were performed with and without metabolites where greater than 25% of metabolite values were below the LOQ. Similar results were obtained with each (data not shown), hence models inclusive of all analytes are presented.

For modeling insulin action components (SI, AIRg, and DI) as outcomes, factors retained in PCA were used in linear regression using backwards stepwise variable selection. SI, AIRg, and DI were logarithmically transformed prior to analyses to approximate a normal distribution, and analyses were controlled for age, gender, and waist circumference. To determine if gender differences exist for those factors found related to insulin action, gender interactions were evaluated. First, full models were fit including each of the independently related factors and each gender*related factor interaction term. If none of the gender interaction terms was found significant, these terms were removed, and the main effects model was refit. If any of the gender interactions were found significant, then stratified main effects models were evaluated. Statistics were performed using SAS Enterprise Guide v8.2 (SAS Institute, Cary, NC) with statistical significance established as P < 0.05.

**RESULTS**

The mean age of this study population was 51.2 ± 7.7 years. Of the 73 subjects, 35 (48%) were women and 38 (52%) were men. Fifty-eight (79%) were Caucasian, 12 (16%) were African-American, 2 (3%) were Asian, and 1 (1%) was Hispanic. The median SI was 2.88 with an inter-quartile range (IQR) from 1.84 to 5.61 X 10^-5 min^-1/[pmol/L]. The median AIRg was 354.9 (IQR=183.6-529.1) pmol/L, and median DI was 1237.3 (IQR=583.8-1732.2) X 10^-5 min^-1.

On-line Appendix Table 1 (which is available at http://care.diabetesjournals.org) demonstrates median values and ranges for concentrations of metabolic intermediates.

Principal components analysis (PCA) was used to reduce the large number of circulating metabolic intermediates into a
smaller number of “factors” containing metabolic intermediates that were highly correlated with one another. Table 1 shows the constituent metabolites for each of the 19 retained factors. As shown in Table 1, the metabolic constituents for each factor were biologically related, such that a biological description for each factor could be applied (see Table 1). The first five factors represented a majority of the variance in the dataset and were summarized as factors containing 1) medium- and long-chain acylcarnitines, 2) fatty acids and by-products of fatty-acid oxidation, 3) long-chain acylcarnitines and acetyl carnitine, 4) large neutral amino acids and uric acid, and 5) medium-chain acylcarnitines and glucose.

After reducing the complexity of the metabolic intermediates into 19 factors of related metabolites, we sought to determine whether these factors could predict SI. Independent of age, gender, and waist circumference, three of these factors were associated with SI and accounted for 63% of its variance (see Table 2). Of these three factors, the one most associated with SI was the factor containing large neutral amino acids. Being inversely associated with SI, this single factor predicted 26% of the variance in insulin sensitivity (P<0.0001, Figure 1). These findings are consistent with another recent study from our group in which a branched-chain amino acid (BCAA)-related factor that included leucine/isoleucine, valine, phenylalanine and tyrosine was the one most strongly associated with a different measure of insulin sensitivity (homeostasis model assessment index [HOMA]) in a cohort of 73 obese and 67 lean subjects(7).

When evaluating predictors of pancreatic response, we found that independent of age, gender, and waist circumference, a metabolic factor containing fatty acids and by-products of fatty acid oxidation was inversely related to AIRg. This model accounted for 28% of the variance in pancreatic response (Table 2), and alone this factor accounted for 12% of the variance in AIRg (P<0.002, Figure 1). Since an appropriate pancreatic response should vary based on tissue insulin sensitivity, we also sought to better understand predictors of an appropriate pancreatic response, as represented by DI. We were able to explain 39% of the variance in the DI with a model containing age, gender, waist circumference and three metabolic factors (Table 2). Inverse associations were seen for DI and factors containing free fatty acids (Figure 1), large neutral amino acids (Figure 1), and medium chain acylcarnitines and glucose. Additionally, age was independently and inversely associated with DI. Body composition, as measured by waist circumference, was an independent predictor of both SI and AIRg, but not DI.

We also wished to explore gender differences in predictors of insulin action due to previous observations of gender-specific effects of metabolic factors on measures of insulin action. For SI, we observed a significant interaction between gender and the factor composed of glutamine and glutamate, factor 7 (P<0.03). Using gender-stratified analyses to further elucidate this gender interaction (On-line Appendix Table 2), we observed that, for men, waist circumference, factors 4, 7, and 8 remained significant independent predictors of insulin sensitivity and accounted for 64% of the variance in SI (model P<0.0001; On-line Appendix Table 2). However, for women, factor 7 was not predictive of SI, while waist circumference, factors 4 and 8 remained independent predictors of SI (model P<0.0001, model R^2= 0.61, On-line Appendix Table 2).

There was no significant interaction between gender and factor 2 for the relationship with AIRg (P=0.35), and thus, stratified analyses were not performed for this
measures of insulin action. When evaluating gender differences in metabolic relationships for DI, we observed a significant interaction between gender and factor 5 (P<0.01). In gender-stratified analyses, factor 4 was the only significant predictor of DI for men (model P<0.0001; Online Appendix Table 2). In contrast, in women, factor 4 was not independently related to DI, but factors 5 and 2 remained significant independent predictors of DI (model P<0.0001; Online Appendix Table 2).

CONCLUSIONS

Our objective was to determine whether circulating metabolic intermediates, as measured with a mass-spectrometry-based platform, are associated with insulin action in a mixed-gender population at risk for, but without overt type 2 diabetes. Using a principal components analytic strategy to reduce the dimensionality of the large number of metabolic variables, we observed several components of insulin action to be independently operative in this population. A single factor containing large neutral amino acids was inversely related to both SI and DI. Also, a factor containing free fatty acids and by-products of fatty-acid oxidation was inversely related to both AIRg and DI. Thus, both large neutral amino acids and fatty acids might contribute to progression to type 2 diabetes and might exhibit differential contributions for insulin action for each gender.

The potential for amino acids to confer insulin resistance has been recognized for some time (8). As with many obesity related derangements, amino acid-induced insulin resistance likely results from mechanisms that have evolved to operate in a low calorie, high activity environment now functioning in a high calorie, low activity environment (9). In a low calorie environment where high protein meals are infrequent, it is not surprising that large neutral amino acids would promote an anabolic state by, inhibiting proteolysis and directly stimulating protein synthesis (10). Similarly, elevated concentrations of amino acids produce insulin resistance by disrupting insulin-mediated glucose uptake pathways resulting in reduced glucose uptake and glycogen synthesis (11). Both stimulation of protein synthesis and inhibition of insulin stimulated glucose uptake occur at the level of the mammalian target of rapamycin (mTOR) (12), a key nodal point in signaling for protein synthesis (13) and insulin stimulated glucose uptake (10; 12). This coordinated promotion of protein synthesis and disruption of glucose uptake pathways would function well with occasionally elevated amino acid concentrations. However, in obesity, elevated concentrations of amino acids are sustained even in the fasting state (8) promoting sustained insulin resistance and, in the presence of other pathologic aberrations, progression to diabetes. Recently, compelling support for the idea that these elevations could be related to pathophysiology was provided by findings that BCAA and several related amino acids and metabolites were elevated in obese, insulin resistant subjects compared to lean controls, and these concentrations were linearly related to HOMA (7). Further, in rats, a high fat diet supplemented with BCAA produced insulin resistance, whereas supplementation of normal chow did not, and the insulin resistance provoked by high fat/BCAA feeding was reversed with administration of the mTOR inhibitor, rapamycin (7). While recognizing that other mechanisms of insulin resistance are also operative with similar teleological explanations, our work clearly supports older as well as new data that relate insulin resistance and concentrations of large neutral amino acids at the population level and in a mixed gender population.

In addition to insulin resistance, a defective beta cell compensatory response is
critical to the development of type 2 diabetes. Similar to the detrimental effects of chronically elevated amino acids on skeletal muscle, emerging evidence suggests that chronic lipid exposure plays a key role in molecular events culminating in beta cell failure (2). In beta cells, lipid oxidation to acetyl CoA activates pyruvate carboxylase, and initiates a pyruvate cycle which results in an increase in concentrations of molecules that amplify insulin secretion. Thus, in healthy, fasting humans, acutely elevated free fatty acids promote beta cell secretion of insulin in order to suppress rampant adipocyte lipolysis and prevent subsequent ketoacidosis (2). As insulin resistance develops, elevated concentrations of free fatty acids promote greater insulin secretion to compensate for insulin resistance, contributing to the well-recognized consequence of hyperinsulinemia. However, sustained exposure to elevated concentrations of fatty acids and chronic activation of pyruvate carboxylase results in a dampening of this pathway’s response to glucose (2; 14) and deficits in beta cell insulin secretion (15-17). Also, this qualitative defect is likely compounded by beta cell apoptosis and a quantitative reduction in beta cells driven by increased oxidative and endoplasmic reticulum stress that occurs as a result of an overload of beta cell lipid metabolism (reviewed in (2; 15)). We observed that a factor containing free fatty acids and byproducts of fatty-acid oxidation was inversely associated with the acute pancreatic response and the pancreatic response when accounting for insulin sensitivity (DI). Our findings show that a poorer compensatory response in insulin production is associated with higher concentrations of circulating fatty acids, potentially supporting a toxic effect of lipids on beta cells in prediabetic subjects such as those included in the current study.

In addition to evaluating relationships between circulating metabolites and measures of insulin action, we also explored gender differences in relationships between circulating metabolites and insulin action. We observed that for men, insulin sensitivity was most related to the factor containing large neutral amino acids and another containing glutamine and glutamate. For women, concentrations of these two sets of metabolites were much less strongly related to insulin sensitivity, but waist circumference and a factor containing glycine and serine were most related. Additionally, the inverse relationship between concentrations of fatty acids and the appropriate pancreatic response (DI) was more robust for women than men. We find these gender differences intriguing in light of emerging evidence that supports gender differences in development of insulin resistance and diabetes (reviewed in (18)). Prior to adolescence, girls are more insulin resistant than boys, but during adolescence, a shift occurs such that in adulthood, women are more insulin sensitive than men (19). While several studies have shown that both male rats (20) and men (21) are more susceptible than women and female rats to fatty acid induced insulin resistance, less work has focused on examining gender differences in relationships between amino acids and insulin resistance.

It is notable that most of the work examining branched chain amino acids in the context of obesity and insulin resistance have been performed predominantly in men (8; 11; 13). Additionally, prior investigations have shown that men are more likely to develop insulin resistance as a consequence of low birth weight (22) and gestational protein availability (23) and exhibit stronger relationships between the insulin-like growth factor axis and insulin sensitivity (24). Such reports lead us to hypothesize that in men, gestational programming, which is designed to meet greater anabolic demands and that operates under abundant amino acid exposure later in life, drives our findings of a stronger
relationship between amino acid concentrations and insulin resistance. Our findings that women might be more susceptible to beta cell lipotoxicity could be related to observed gender differences in hormone sensitive lipase mediated regulation of lipolysis in pancreatic beta cells (25). Most important, the observed gender differences in these relationships emphasize the critical nature of carefully attending to gender differences and hormonal influences on insulin action in our efforts to uncover the pathogenesis of type 2 diabetes.

We recognize that this investigation has several limitations. The moderate sample size and cross-sectional nature of this investigation may limit the applicability of our findings. While this cross-sectional design allows only inferences about causality, we have taken advantage of this design to confirm the findings of prior physiologic studies in humans at a population level. Additionally, our moderate sample size did not allow for exploration of race or ethnic variations in predictors of insulin action. Similarly, we were unable to account for other obvious influences on insulin action such as genetic ones. However, we were able to explore gender differences in both insulin resistance and beta cell dysfunction. Also, we were able to demonstrate the applicability of a targeted, mass-spectrometry-based platform to a clinical sample of modest size. Rather than presenting a large number of correlations between biological assays and clinical measurements, we have illustrated that PCA is a means of data complexity reduction with biologic plausibility.

Thus, in a mixed-gender population at risk for, but without overt type 2 diabetes, concentrations of large neutral amino acids were related to insulin resistance, and concentrations of free fatty acids and by-products of fatty-acid oxidation were related to an impaired pancreatic response. There was also a gender difference in the strength of these relationships, such that men appeared more susceptible to amino acid-induced insulin resistance and women more vulnerable to lipid-mediated beta cell toxicity. While these findings merit validation in other cohorts, they support the recognition that metabolic processes which have evolved to sustain demands in a low calorie environment produce many of the aberrations characteristic of type 2 diabetes when metabolic fuels are in excess.

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Table 1: Results of Principal Components Analysis: Key metabolites within each retained factor (i.e. metabolites with factor load $\geq |0.4|$) and an overall description of each factor are presented. Italicized metabolites represent those with a factor load $\geq |0.4|$ on a second factor.

| Factor | Metabolites within Factor | Description | Eigen-value | Variance | Cumulative Variance |
|--------|---------------------------|-------------|-------------|----------|---------------------|
| 1      | C8 C5-DC C10:1 C10 C12:1 C12 C14:2 C14:1 C14 C16 C8:1-OH/C6:1-DC C8:1-DC C16:2 C16:1 C18:2 | Medium- and long-chain acylcarnitines | 13.1 | 0.17 | 0.17 |
| 2      | FA-C14:0 FA-C16:1 FA-C16:0 FA-\alpha-C18:3 FA-C18:2 FA-C18:1 FA-C18:0 FA-C22:6 | Free fatty acids and by-products of fatty-acid oxidation | 9.6 | 0.13 | 0.30 |
| 3      | C2 C6-DC C10-OH/C8-DC C12-OH/C10-DC C14:1-OH C18 C18:1 C18:2 C14-OH/C12-DC C18:1-OH C16:1-OH/C14:1-DC C16 | Long-chain acylcarnitines and C2-acylcarnitine | 6.4 | 0.09 | 0.39 |
| 4      | Proline Valine Leucine/Isotocine Methionine Phenylalanine Tyrosine Uric acid Histidine | Large neutral amino acids and uric acid | 4.3 | 0.06 | 0.44 |
| 5      | C8:1 C10:3 Glucose | Medium-chain acylcarnitines and glucose | 3.5 | 0.05 | 0.49 |
| 6      | C3 C4/Ci4 C5's | Short-chain acylcarnitines | 3.1 | 0.04 | 0.53 |
| 7      | Glutamate/Glutamine Hydroxybutyrate Ketones Glucose | Glutamate/Glutamine | 2.7 | 0.05 | 0.57 |
| 8      | Glycine Serine | One-carbon metabolism | 2.3 | 0.03 | 0.60 |
| 9      | C20 C16-OH/C14-DC C18:1-DC | Long-chain and hydroxy or dicarboxy acylcarnitines | 2.1 | 0.03 | 0.63 |
| 10     | Alanine Lactate | Alanine and lactate | 2.0 | 0.03 | 0.66 |
| 11     | C6 C5OH/C3-DC | Short-chain and hydroxy or dicarboxy acylcarnitine | 1.7 | 0.02 | 0.68 |
| 12     | Citrulline Arginine C10:2 C18-OH/C16-DC | Urea cycle, medium-chain acylcarnitine, and hydroxy or dicarboxy acylcarnitine | 1.7 | 0.02 | 0.70 |
| 13 | C20:4          | Arachidonoyl carnitine | 1.5 | 0.02 | 0.72 |
| 14 | Ornithine  FA-C20:4 (neg) | Ornithine and arachidonic acid | 1.5 | 0.02 | 0.74 |
| 15 | C5:1  C18:2-OH (neg) | Acylcarnitines | 1.6 | 0.02 | 0.76 |
| 16 | C22  C4-OH (neg) | Acylcarnitines | 1.3 | 0.02 | 0.78 |
| 17 | Aspartate/Asparagine | Aspartate/Asparagine | 1.3 | 0.02 | 0.79 |
| 18 | C18-OH/C16-DC  C22:6 | Hydroxy or dicarboxy acylcarnitine | 1.2 | 0.02 | 0.81 |
| 19 | Histidine  C7-DC | Histidine and dicarboxy acylcarnitine | 1.1 | 0.01 | 0.82 |
Table 2: Linear regression models for measures of insulin action using backward stepwise variable selection controlling for age, gender, and waist circumference. Listed metabolite factors are ones that remained significant in multivariable regression models.

| Parameter                                             | Estimate | Standard Error | F Value | P Value |
|-------------------------------------------------------|----------|----------------|---------|---------|
| **S₁ Model:** $R^2_{S₁} = 0.63, P<0.0001$              |          |                |         |         |
| Factor 4: Large neutral amino acids and uric acid     | -0.123   | 0.027          | 21.41   | <.0001  |
| Waist circumference                                   | -0.014   | 0.003          | 16.28   | 0.0001  |
| Factor 8: Glycine and serine                         | 0.091    | 0.025          | 13.57   | 0.0005  |
| Factor 7: Glutamate/Glutamine (ketones and glucose)   | -0.093   | 0.027          | 11.95   | 0.001   |
| **AIRg Model:** $R^2_{AIRg} = 0.28, P<0.0002$         |          |                |         |         |
| Factor 2: Fatty acids and by-products of fatty-acid oxidation | -0.088   | 0.043          | 4.07    | 0.048   |
| **DI Model:** $R^2_{DI} = 0.39, P<0.0001$             |          |                |         |         |
| Factor 4: Large neutral amino acids and uric acid     | -0.145   | 0.044          | 10.56   | 0.002   |
| Factor 2: Free fatty acids and by-products of fatty-acid oxidation | -0.131   | 0.046          | 8.06    | 0.006   |
| Age                                                   | -0.014   | 0.006          | 5.92    | 0.018   |
| Factor 5: Medium-chain acylcarnitines and glucose     | -0.092   | 0.042          | 4.83    | 0.032   |

$R^2$ values reflect those for models presented and include effects of age, gender, and waist circumference. Only significant predictors are presented and individual $R^2$ values are discussed in text.
Figure 1: Relationships between Factor Scores and Measures of Insulin Action

A. Relationship between Factor 4 Score and Insulin Sensitivity ($S_i$)
B. Relationship between Factor 2 Score and Acute Insulin Response to Glucose (AIRg)
C. Relationship between Factor 4 Score and Disposition Index (DI)
D. Relationship between Factor 2 Score and DI