Heart rate variability (HRV) is a noninvasive measure reflecting autonomic cardiac function that independently predicts death and arrhythmic complications in apparently healthy middle-age and elderly subjects (Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology 1996; Tsuji et al. 1994, 1996). Disturbances in autonomous nervous system function reflected by decreased HRV may represent one pathway by which tobacco smoke, including second-hand smoke (SHS), and air pollutants affect cardiovascular morbidity and mortality. The mechanisms are poorly understood.

OBJECTIVES: We investigated the hypothesis that oxidative stress alters cardiac autonomic control. We studied the association of polymorphisms in oxidant-scavenging glutathione S-transferase (GST) genes and their interactions with SHS and obesity with HRV.

METHODS: A total of 1,133 nonsmokers > 50 years of age from a population-based Swiss cohort underwent ambulatory 24-hr electrocardiogram monitoring and reported on lifestyle and medical history. We genotyped GSTM1 and GSTT1 gene deletions and a GSTP1 (Ile105Val) single nucleotide polymorphism and analyzed genotype-photocarboy associations by multiple linear regression.

RESULTS: Homozygous GSTT1 null genotypes exhibited an average 10% decrease in total power (TP) and low-frequency-domain HRV parameters. All three polymorphisms modified the cross-sectional associations of HRV with SHS and obesity. Homozygous GSTM1 null genotypes with > 2 hr/day of SHS exposure exhibited a 26% lower TP [95% confidence interval (CI), 11 to 39%], versus a reduction of ~5% (95% CI, 22 to 17%) in subjects with the gene and the same SHS exposure compared with GSTM1 carriers without SHS exposure. Similarly, obese GSTM1 null genotypes had, on average, a 22% (95% CI, 12 to 31%) lower TP, whereas with the gene present obesity was associated with only a 3% decline (95% CI, -15% to 10%) compared with nonobese GSTM1 carriers.

CONCLUSIONS: GST deficiency is associated with significant HRV alterations in the general population. Its interaction with SHS and obesity in reducing HRV is consistent with an impact of oxidative stress on the autonomous nervous system.

activity in the general population, we have investigated the association between polymorphisms in \textit{GSTM1}, \textit{GSTT1}, and \textit{GSTP1} and changes in HRV in male and female participants in the population-based SAPALDIA cohort (Swiss Cohort on Air Pollution and Lung and Heart Disease in Adults) ≥ 50 years of age. To indirectly test whether the effects of SHS were mediated by oxidative stress, we also assessed the interaction of SHS with \textit{GSTM} polymorphisms and obesity.

\textbf{Materials and Methods}

\textbf{Study population.} SAPALDIA was designed to measure the health effects of air pollutants and has been previously described (Ackermann-Liebrich et al. 2005; Downs et al. 2007; Martin et al. 1997). Briefly, random samples of the Swiss population were recruited from eight areas featuring distinct geographic and environmental conditions. Participants were examined in 1991 and in 2001–2003. A random sample of follow-up participants ≥ 50 years of age participated in a 24-hr electrocardiogram recording (\textit{n} = 1,837) (Felber Dietrich et al. 2006, 2007), including 1,133 nonsmoking subjects [see Supplemental Material (http://www.ehponline.org/members/2008/11402/suppl.pdf) for exclusion criteria]. The study protocol complied with all applicable ethical regulations. Participants gave written informed consent before the study. The study was approved by the Ethical Committee of the Swiss Academy of Medical Sciences and the eight cantonal ethical committees.

\textbf{Interview, body mass index, and blood pressure.} SHS exposure was assessed at the in-person interview by asking subjects how many hours per day they were exposed to other people’s tobacco smoke (\textit{a}) at home, (\textit{b}) at the workplace, (\textit{c}) in bars and restaurants, or (\textit{d}) elsewhere. We focused on SHS exposure at home and work because these two sources dominate overall exposure in most subjects. We classified subjects as not exposed, exposed ≤ 2 hr/day, or exposed > 2 hr/day (Felber Dietrich et al. 2007). Weight, height, and body mass index (BMI; kg/m\(^2\)) were based on measuring participants without them wearing any shoes or coats. Blood pressure was measured at rest in the sitting position on the left upper arm by an automatic device (705CP, OMRON, Steinhausen, Switzerland).

\textbf{HRV parameters.} For 24-hr electrocardiogram (Holter) recording, digital devices (Aria, Del Mar Medical Systems, Irvine, CA, USA) with a frequency resolution of 0.05–40 Hz and a resolution of 128 samples/sec were used (Felber Dietrich et al. 2006, 2007). The records were hooked up after the interview. Participants were asked to follow their regular daily life and to fill in a time–activity diary during recording time. Mean duration of the recordings was 22.3 ± 2.1 hr. All recordings were scanned through a StrataScan 563 (Del Mar). Mean heart rate per minute was derived from Holter measurements. Spectral analysis was performed by the fast Fourier transform method. Here we focus on the frequency-domain variables because they allow resolution of total HRV [total power (TP); ≤ 0.40 Hz] into a component primarily reflecting parasympathetic stimulation [high-frequency (HF) power; 0.15–0.40 Hz] and a component reflecting both sympathetic and parasympathetic influences [low-frequency (LF) power; 0.04–0.15 Hz] [for methodological details, see Supplemental Material (online at http://www.ehponline.org/members/2008/11402/suppl.pdf); for results on time-domain parameters SDNN (standard deviation of all normal-to-normal intervals), SDANN (deviations of the normal-to-normal R-R period), and rMSSD (square root of the mean squared differences of successive R-R intervals), see Supplemental Material, Tables 1 and 2].

\textbf{Blood markers and genotype.} All subjects were genotyped for \textit{GSTM1} (UniGene ID Hs.301961; UniGene 2008a) and \textit{GSTT1} (UniGene Hs.268573; UniGene 2008b) gene deletions and a single nucleotide polymorphism (SNP) in \textit{GSTP1} (UniGene Hs.523836; UniGene 2008c) leading to the amino acid substitution Ile105Val, as previously described (Imboden et al. 2007) [for details, see Supplemental Material (online at http://www.ehponline.org/members/2008/11402/suppl.pdf)].

\textbf{Results}

Table 1 presents characteristics of the study population, which have also been reported in

\begin{table}
\begin{tabular}{ll}
\hline
Characteristic & Value \\
\hline
Total [no. (%)] & 1,133 (100.0) \\
Female sex [no. (%)] & 594 (52.4) \\
Age [years (mean ± SD)] & 60.6 ± 6.3 \\
BMI [kg/m\(^2\) (mean ± SD)] & 26.6 ± 4.2 \\
≥ 30 kg/m\(^2\) [no. (%)] & 223 (19.7) \\
SHS exposure [no. (%)] & \\
None & 956 (84.5) \\
≥ 2 hr/day & 99 (8.7) \\
> 2 hr/day & 78 (6.9) \\
Diabetes [no. (%)] & 41 (3.6) \\
Medication [no. (%)] & \\
ACE inhibitor & 135 (11.9) \\
Antiarhythmics, classes I + III & 70 (6.2) \\
Calcium-channel blocker & 5 (0.4) \\
Diuretics & 53 (4.7) \\
Diuretics & 42 (3.7) \\
Sympathomimetics & 27 (3.3) \\
Uric acid [μmol/L (mean ± SD)] & 323.6 ± 81.6 \\
High-sensitivity C-reactive protein [mg/L (mean ± SD)] & 2.5 ± 5.8 \\
Non-HDL cholesterol [mmol/L (mean ± SD)] & 4.7 ± 1.1 \\
Blood pressure [mmHg (mean ± SD)] & \\
Systolic & 132.5 ± 19.3 \\
Diastolic & 81.9 ± 10.6 \\
Heart rate [bpm (mean ± SD)] & 73.5 ± 9.0 \\
HRV [mean ± SD] & \\
TP [msec\(^2\)] & 4583.1 ± 2902.5 \\
TF power [msec\(^2\)] & 304.0 ± 275.9 \\
HF power [msec\(^2\)] & 114.4 ± 235.0 \\
SDNN [msec] & 138.7 ± 36.5 \\
SDANN [msec] & 125.6 ± 35.0 \\
rMSSD [msec] & 26.2 ± 14.9 \\
Genotypes [no. (%)] & \\
\textit{GSTM1} deletion & 594 (52.4) \\
\textit{GSTT1} deletion & 199 (17.6) \\
\textit{GSTP1} & \\
Ile/Ile & 550 (48.5) \\
Ile/Val & 485 (42.8) \\
Val/Val & 98 (8.7) \\
\hline
\end{tabular}
\end{table}

\textbf{Statistical analysis.} We assessed the association of log-transformed HRV with \textit{GSTM} genotypes, obesity, and SHS exposure by multiple regression analyses adjusting for study area, age (and its square), sex, diabetes, beta-blocker intake, and fruit intake. We present results as percent change in HRV parameters compared with the respective reference groups. To assess the interactions between SHS, \textit{GSTM} genotypes, and obesity, we calculated trend tests by entering cross-categorized variables into the respective regression models. We coded the cross-categorized variables as 1 if both at-risk characteristics were absent, 2 if only one at-risk characteristic was present, and 4 if both at-risk characteristics were present in a subject. We performed statistical analysis using the software package SAS version 8.2 (SAS Institute, Inc., Cary, NC, USA) [for details, see Supplemental Material (http://www.ehponline.org/members/2008/11402/suppl.pdf)].
more detail elsewhere (Felber Dietrich et al. 2007). In brief, 52% of the subjects included in the study were females. Mean age was 60.6 (SD 6.3) years, and mean BMI was 26.6 (4.2) kg/m². Non-log-transformed means (SDs) for the different frequency-domain HRV parameters were TP, 4,583.1 msec² (2,902.5); HF, 114.4 msec² (235.0); and LF, 304.0 msec² (275.9). SHS exposure either at work or at home was reported by 16% of the participants. In the present subpopulation of nonsmokers, 52% and 18% of subjects exhibited homozygous GSTM1 and GSTT1 gene deletion, respectively. Genotype distribution for the GSTP1 Ile105Val SNP was 49% (Ile/Ile), 43% (Ile/Val), and 8% (Val/Val).

Table 2 presents the independent associations of GST genotypes, SHS, and obesity with changes in LF, HF, and TP HRV parameters. We observed no association for any of the predictors with HF values. GSTTI1 deficiency, > 2 hr/day of SHS exposure, and obesity were each independently associated with lower TP and LF, and there was a trend toward an association of GSTP1 (Ile105Val) with TP. TP and LF were each 10% lower among subjects homozygous for GSTTI1 gene deletion compared with participants without the deletion (p = 0.02 and 0.04). The associations between HRV and GSTP1 were consistent with the GSTTI1 findings but did not reach statistical significance. GSTM1 deficiency was not associated with changes in any HRV parameter. SHS (−17.6%, p = 0.006) and obesity (−15.0%, p = 0.0003) were associated with larger reductions in overall HRV (TP) than were the genotypes. The association of GST genotypes, obesity, and SHS with HRV time-domain parameters were generally consistent in direction with those observed for frequency-domain parameters, but reached statistical significance only for the obesity association with both SDNN and SDANN [see Supplemental Material, Table 1 (http://www.ephonline.org/members/2008/11402/suppl.pdf)].

The results presented above were unaltered when we adjusted them for any of the additional potential confounders listed under “Statistical analysis” (data not shown). Additional control for heart rate and systolic or diastolic blood pressure also did not materially alter these results. Additional analysis of HRV restricted to the sleep period according to diary information showed results similar to those achieved in the 24-hr analyses. On average, LF power was lower at night by 11.1% (p = 0.03) in the GSTTI1-deficient group compared with the reference group.

Discussion

We found associations between common GST gene variants that are involved in oxidant defense and HRV in the general population. Participants missing both copies of the GSTTI1 gene had, on average, 10% lower overall and LF-domain HRV. GSTM1 deficiency and the GSTP1 Ile105Val SNP were not independently associated with HRV changes, but we identified interactions between all three GST polymorphisms and exposure to SHS for effects on HRV. Combined with the interaction of SHS with obesity, a condition known to increase systemic oxidative stress, this provides support for the hypothesis that SHS affects HRV through oxidative stress pathways. This in turn implies that oxidative stress is an important modifier of the autonomic control of the heart, a hypothesis that has received little attention until recently.

The hypothesis of oxidative stress being a relevant pathophysiological mechanism underlying individual variation in the functioning of the autonomous nervous system, and therefore HRV, is supported by (a) genetic polymorphisms related to oxidative defenses (Forberg et al. 2001; Hayes and Strange 2000; Park et al. 2006) affecting HRV; (b) conditions likely to increase oxidative stress, such as obesity (Keaney et al. 2003) and SHS (Zhang et al. 2002), decreasing HRV; and (c) prooxidative conditions such as obesity and SHS interacting with genetic polymorphisms related to oxidative defenses.

Epidemiologic support for an association between oxidative stress and the autonomic control of the heart is still limited, but recent evidence is supportive of this hypothesis. Data in men from the Normative Aging Study recently provided strong evidence that oxidative stress may be a key pathway for the adverse effects of combustion particles on HRV (Schwartz et al. 2005). The association between fine PM and reduced HRV was restricted to persons missing the GSTM1 gene and persons likely to have greater than average baseline systemic inflammation and oxidative stress, such as the obese. Statins, a widely prescribed class of lipid-lowering drugs with substantial antiinflammatory and antioxidant activity, protected GSTM1-deficient subjects against the effects of fine PM (Schwartz et al. 2005). One key difference in our study is that we aimed to assess the effect of a chronic exposure (SHS, obesity) on baseline HRV, rather than an acute one. Although some of the observed associations can still be attributed to acute effects due to collinearity.

Table 2. Percent difference (95% CI) in HRV parameters according to GST genotypes, SHS, and obesity: the SAPALDIA cohort study.

<table>
<thead>
<tr>
<th>Genotype/exposure</th>
<th>LF power</th>
<th>HF power</th>
<th>TP</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSTM1 Deletion vs. no deletion</td>
<td>−1.7 (−9.3 to 6.4)</td>
<td>−1.6 (−11.2 to 9.0)</td>
<td>−2.6 (−9.1 to 4.4)</td>
</tr>
<tr>
<td>GSTP1 Ile105Val</td>
<td>−10.7 (−19.6 to −0.7)</td>
<td>−3.4 (−15.6 to 10.5)</td>
<td>−10.4 (−18.2 to −1.9)</td>
</tr>
<tr>
<td>Ile/Ile vs. Val/Val</td>
<td>−7.9 (−20.1 to 6.2)</td>
<td>−8.6 (−23.8 to 9.7)</td>
<td>−10.6 (−20.9 to 1.1)</td>
</tr>
<tr>
<td>≤ 2 hr/day vs. none</td>
<td>−10.3 (−22.3 to 3.5)</td>
<td>−13.0 (−27.5 to 4.6)</td>
<td>−4.3 (−15.5 to 8.2)</td>
</tr>
<tr>
<td>&gt; 2 hr/day vs. none</td>
<td>−16.4 (−28.8 to −1.9)</td>
<td>−2.6 (−20.6 to 19.6)</td>
<td>−17.6 (−28.3 to −5.4)</td>
</tr>
<tr>
<td>Obesity ≥ 30 vs. &lt; 30 kg/m²</td>
<td>−19.5 (−27.4 to −10.6)</td>
<td>−5.0 (−16.7 to 8.4)</td>
<td>−15.0 (−22.2 to −7.2)</td>
</tr>
</tbody>
</table>

*Adjusted for study area, sex, age and (age²), fruit intake, diabetes, and beta-blocker intake and mutually adjusted for each other. Homozygous gene deletion.
between chronic and acute exposure, the association with chronic exposure suggests an ongoing and not a transitory impact on HRV, which may have more public health relevance. On the other hand, the similarity between SHS and ambient PM is sufficiently high that the finding of interactions between GSTM1 status and obesity with these exposures in two separate cohorts argues against this being a chance finding.

The association of chronic stimuli such as obesity, insulin resistance, and diabetes with reduced HRV (Furukawa et al. 2004) is also compatible with an ROS impact on the autonomic nervous system. In nondiabetic human subjects, fat accumulation and obesity are closely correlated with markers of systemic oxidative stress (Keaney et al. 2003; Olusi 2002). Diabetic patients are known to have elevated oxidative stress levels, and they also exhibit increased susceptibility to the effect of air pollution on HRV (Zanobetti and Schwartz 2002). Chronic administration of the antioxidant vitamin E in a double-blind randomized controlled trial in patients with type 2 diabetes and cardiac autonomic neuropathy improved the ratio of the cardiac sympathetic to parasympathetic tone (Manzella et al. 2001). Marine- and plant-derived omega-3 fatty acid supplementation in elderly nursing home residents was associated with a significant increase in HRV (Holguín et al. 2005). The omega-3 fatty acid effects are possibly attributable in part to their antioxidative properties (Mori et al. 2003).

The exact mechanisms by which ROS and associated inflammatory mediators affect the autonomous nervous system and its correlates HRV are still poorly understood and likely complex. Oxidants and inflammatory mediators can act directly in the brain, as evidenced by the involvement of oxidative stress in various neurodegenerative diseases such as Alzheimer’s and Parkinson’s disease (Chong et al. 2005). Inflammatory markers, including interleukin-6, are present in the brain, where they can influence the autonomic balance (Jutler et al. 2002). A central nervous system effect of ROS is also compatible with results from a recent investigation in spontaneously hypertensive rats that are characterized by elevated oxidative stress (Girouard et al. 2004).

<table>
<thead>
<tr>
<th>Genotype</th>
<th>Exposure</th>
<th>No.</th>
<th>LF power</th>
<th>HF power</th>
<th>TP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GSTM1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No deletion</td>
<td>No/low SHS</td>
<td>504</td>
<td>Referent</td>
<td>Referent</td>
<td>Referent</td>
</tr>
<tr>
<td>No deletion</td>
<td>High SHS</td>
<td>35</td>
<td>–11.5 (–30.0 to 27.7)</td>
<td>–2.2 (–12.0 to 8.7)</td>
<td>–4.6 (–22.0 to 16.7)</td>
</tr>
<tr>
<td>Deletion†</td>
<td>No/low SHS</td>
<td>551</td>
<td>–1.2 (–8.0 to 7.3)</td>
<td>–5.5 (–30.0 to 27.7)</td>
<td>–0.8 (–7.7 to 6.4)</td>
</tr>
<tr>
<td>Deletion†</td>
<td>High SHS</td>
<td>35</td>
<td>–19.9 (–35.4 to –0.7)</td>
<td>1.6 (–22.8 to 33.9)</td>
<td>26.3 (–38.7 to –11.4)</td>
</tr>
<tr>
<td>p-Value for trend †</td>
<td></td>
<td></td>
<td>0.094</td>
<td>0.08</td>
<td>0.014</td>
</tr>
<tr>
<td>No deletion</td>
<td>Not obese</td>
<td>437</td>
<td>Referent</td>
<td>Referent</td>
<td>Referent</td>
</tr>
<tr>
<td>No deletion</td>
<td>Obese</td>
<td>102</td>
<td>–13.3 (–25.3 to 0.7)</td>
<td>1.6 (–16.2 to 23.0)</td>
<td>–3.0 (–14.7 to 10.4)</td>
</tr>
<tr>
<td>Deletion†</td>
<td>Not obese</td>
<td>473</td>
<td>1.2 (–7.5 to 10.6)</td>
<td>1.0 (–16.2 to 23.0)</td>
<td>2.4 (–5.2 to 10.6)</td>
</tr>
<tr>
<td>Deletion†</td>
<td>Obese</td>
<td>121</td>
<td>–23.5 (–33.4 to –12.0)</td>
<td>–9.4 (–24.2 to 8.2)</td>
<td>–22.1 (–30.9 to –12.1)</td>
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<td>p-Value for trend †</td>
<td></td>
<td></td>
<td>0.16</td>
<td>0.69</td>
<td>0.25</td>
</tr>
<tr>
<td><strong>GSTT1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No deletion</td>
<td>No/low SHS</td>
<td>871</td>
<td>Referent</td>
<td>Referent</td>
<td>Referent</td>
</tr>
<tr>
<td>No deletion</td>
<td>High SHS</td>
<td>63</td>
<td>–17.6 (–30.9 to –1.7)</td>
<td>–3.0 (–22.6 to 15.1)</td>
<td>–21.3 (–32.3 to –8.5)</td>
</tr>
<tr>
<td>Deletion†</td>
<td>No/low SHS</td>
<td>184</td>
<td>–11.1 (–20.2 to –0.7)</td>
<td>–4.1 (–16.7 to 10.3)</td>
<td>–12.1 (–20.0 to –3.5)</td>
</tr>
<tr>
<td>Deletion†</td>
<td>High SHS</td>
<td>15</td>
<td>–16.5 (–41.1 to 18.5)</td>
<td>6.9 (–31.8 to 67.4)</td>
<td>–6.7 (–30.9 to 25.9)</td>
</tr>
<tr>
<td>p-Value for trend †</td>
<td></td>
<td></td>
<td>0.007</td>
<td>0.77</td>
<td>0.002</td>
</tr>
<tr>
<td>No deletion</td>
<td>Not obese</td>
<td>748</td>
<td>Referent</td>
<td>Referent</td>
<td>Referent</td>
</tr>
<tr>
<td>No deletion</td>
<td>Obese</td>
<td>186</td>
<td>–18.1 (–26.7 to –8.4)</td>
<td>–5.3 (–18.0 to 9.3)</td>
<td>–15.1 (–22.9 to –6.4)</td>
</tr>
<tr>
<td>Deletion†</td>
<td>Not obese</td>
<td>162</td>
<td>–8.7 (–18.8 to 2.6)</td>
<td>–3.5 (–16.9 to 12.1)</td>
<td>–10.3 (–19.0 to –0.8)</td>
</tr>
<tr>
<td>Deletion†</td>
<td>Obese</td>
<td>37</td>
<td>–33.1 (–46.7 to –16.0)</td>
<td>–7.3 (–30.8 to 24.0)</td>
<td>–24.5 (–37.9 to –8.1)</td>
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<td></td>
<td></td>
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<td>0.084</td>
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<td><strong>GSTP1, Ile105Val</strong></td>
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</tr>
<tr>
<td>Val/Val</td>
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<td>87</td>
<td>Referent</td>
<td>Referent</td>
<td>Referent</td>
</tr>
<tr>
<td>Ile/Ile,Val</td>
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<td>11</td>
<td>–16.9 (–45.9 to 27.7)</td>
<td>13.4 (–34.6 to 99.5)</td>
<td>–9.4 (–37.2 to 32.0)</td>
</tr>
<tr>
<td>Ile/Ile,Val</td>
<td>No/low SHS</td>
<td>969</td>
<td>–7.9 (–20.7 to 7.0)</td>
<td>–6.5 (–22.9 to 13.3)</td>
<td>–9.7 (–20.6 to 2.7)</td>
</tr>
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<td>p-Value for trend †</td>
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<td></td>
<td>0.020</td>
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<td>Not obese</td>
<td>79</td>
<td>Referent</td>
<td>Referent</td>
<td>Referent</td>
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<tr>
<td>No deletion</td>
<td>Obese</td>
<td>19</td>
<td>–2.2 (–30.7 to 38.0)</td>
<td>6.6 (–31.4 to 58.6)</td>
<td>10.5 (–17.9 to 48.8)</td>
</tr>
<tr>
<td>Deletion†</td>
<td>Not obese</td>
<td>831</td>
<td>–4.1 (–18.1 to 4.7)</td>
<td>–6.3 (–23.5 to 14.7)</td>
<td>–5.5 (–15.7 to 8.4)</td>
</tr>
<tr>
<td>Deletion†</td>
<td>Obese</td>
<td>204</td>
<td>–24.1 (–36.5 to –9.2)</td>
<td>–11.9 (–29.9 to 10.8)</td>
<td>–21.8 (–32.8 to –8.5)</td>
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<td>0.66</td>
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<td><strong>Obesity</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>655</td>
<td>Referent</td>
<td>Referent</td>
<td>Referent</td>
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<tr>
<td>No/low SHS</td>
<td>Obese</td>
<td>200</td>
<td>–1.2 (–18.0 to 16.1)</td>
<td>9.9 (–13.5 to 28.1)</td>
<td>–12.1 (–25.2 to 3.2)</td>
</tr>
<tr>
<td>High SHS</td>
<td>Not obese</td>
<td>55</td>
<td>–3.4 (–17.4 to 13.0)</td>
<td>5.6 (–13.7 to 23.1)</td>
<td>5.4 (–7.9 to 20.7)</td>
</tr>
<tr>
<td>High SHS</td>
<td>Obese</td>
<td>23</td>
<td>–44.4 (–58.9 to –24.8)</td>
<td>–18.6 (–44.9 to 20.0)</td>
<td>–24.1 (–41.5 to –1.5)</td>
</tr>
<tr>
<td>p-Value for trend †</td>
<td></td>
<td></td>
<td>0.002</td>
<td>0.76</td>
<td>0.049</td>
</tr>
</tbody>
</table>

*Adjusted for study area, sex, age and (age)², fruit intake, diabetes, and beta-blocker intake and mutually adjusted for each other. We did not mutually adjust GST polymorphisms for each other. We adjusted GST/SHS models for BMI as a continuous variable, and adjusted GST/obesity models for SHS. †Homozygous deletion. ‡We derived the p-values for trend by entering a cross-categorized variable coded as 1, 2, and 4 for subjects exhibiting 0, 1, or 2 at-risk characteristics, respectively. 

Figure 1. Combined effects (percent change and 95% CI) of GSTM1 genotype [deletion (del) vs. no deletion], obesity (obese vs. not obese), and SHS (high SHS vs. no/low SHS) exposure on TP.
The antioxidants N-acetylcysteine and melatonin restored cardiac baroreflex to normal, but not blood pressure, an effect that could be attributable to a central nervous system ROS effect. Interestingly, these rats were characterized by a primarily sympathetic defect, and our study finds the effects of SHS, obesity, and GST polymorphisms are absent for HF, which reflects a primarily parasympathetic response. Finally, ROS and inflammatory markers may further exacerbate the autonomic disturbances on the heart through peripheral local effects on heart structures (Lee and Widdicombe 2001), because oxidative stress is the most commonly hypothesized mechanism by which several cytotoxic anticancer drugs cause cardiotoxicity (Stone and Godleski 1999). Tracey (2002) describes the central role of the autonomous nervous system in monitoring as well as regulating oxidative stress and inflammation at innervated pulmonary and extrapulmonary sites as the inflammatory reflex. In accordance with the inflammatory reflex model and our results, recent studies in rats intratracheally exposed to urban PM suggested a pulmonary-to-cardiac signaling model with pulmonary oxidants increasing cardiac oxidant concentrations under the strict control of the autonomous nervous system. Cardiac oxidative stress was preventable by both N-acetylcysteine and β1 receptor antagonist pretreatment of these animals (Rhoden et al. 2005).

The respective impact of the different GST polymorphisms on HRV observed in this study further elucidates ROS mechanisms. The GST genes and isozymes exhibit differences in tissue expression as well as substrate specificity (Forshberg et al. 2001; Hayes and Strange 2000). Although liver is the only rich source of the GSTM1 isozyme, where it is the predominant form, GSTP1 and GSTT1 are expressed in various tissues, including heart, brain, lung, and liver (Hayes and Strange 2000; Rowe et al. 1997). The presence of GSTT1 and—statistically nonsignificant—GSTP1 main effects and the absence of a GSTM1 main effect on HRV are consistent with an impact of locally and endogenously produced ROS in lung, heart, brain, and possibly additional organs on the activity of the autonomous nervous system. The hypothesis that endogenously produced oxidative stress affects the nervous system is further supported by the observation that lack of GSTT1, but not of other GST variants, is generally associated with increased susceptibility to brain diseases, including brain tumors and neurodegenerative diseases, even in apparently unexposed individuals (Landi 2000).

The modifying effect of GSTM1 for the association of SHS with HRV suggests that these exposures cause systemic oxidative stress that is being scavenged by GSTM1 in the liver. The modification of the SHS effect by GSTM1 is consistent with previous studies on the association between SHS, GST polymorphisms, and lung cancer in never smokers (Wenzlaff et al. 2005) and may reflect the additional impact of GSTM1 on liver metabolism of tobacco-derived electrophiles (Hayes and Strange 2000; Landi 2000; Rowe et al. 1997). The modifying effect of GSTP1 variants suggests that oxidative stress in target tissues other than liver is also important for the effects of SHS. The observation of subadditive effects of GSTT1 and SHS, in contrast to the superadditive effects of GSTT1 and obesity, suggest that some specific components of SHS drive the direction of the interaction. Depending on the substrate, GSTT1-catalyzed reactions can actually increase toxicity (Landi 2000). What that component is remains to be determined.

This study has a number of limitations. In all genetic studies, the prevalence of the polymorphism can limit power. A greater concern in this study is the 6.9% prevalence rate for high SHS exposure, which clearly limits power in gene-by-environment interactions. An additional limitation of this study is its cross-sectional design. We recorded electrocardiograms once for each subject. The future longitudinal assessment at the next follow-up examination will allow for improved adjustment of within-subject variation and allow us to examine differences in baseline autonomic function over time. The aging of the cohort will provide information on the combined impact of modifiable and genetic factors on the course of HRV decline and on the incidence of cardiac diseases. Finally, although the reported associations were comparable for frequency- and time-domain parameters, they were generally stronger and more consistent in the frequency domain.

However, the focus on frequency-domain parameters seems justified. First, the frequency-domain parameter HF captures the vagal, parasympathetic response more clearly than does rMSSD. Second, the Fourier transformation for TP, but not SDNN, is for a specified frequency range that trims off some ultra-HF signals. Extending the upper limit of the HF component, which is implicitly lacking in SDNN, beyond 0.4 Hz would be applicable only to extreme tachycardia of >24 respiratory cycles per minute. This is linked to extreme sympathetic overdrive, under which it is rather difficult to interpret the HF component. Moreover, because the cardiac period signal is discrete rather than continuous, it is difficult to properly estimate respiratory arrhythmia under such conditions of very fast tachycardia.

In conclusion, our results are consistent with an important role of oxidative stress in the autonomic control of the heart and, possibly, in individual variability in autonomous nervous system activity. If confirmed by additional studies specifically investigating the association between systemic oxidative stress markers and HRV, these findings have substantial public health relevance. Tsuji et al. (1996) suggested that a 1-SD reduction in overall HRV was associated with a relative risk of 1.47 for cardiac events over 3.5 years of follow-up. Although differences in study design preclude a quantitative risk estimate, the observed reduction in overall HRV in subjects with SHS exposure (>2 hr) and either obesity, GSTM1 deletion, or GSTP1 substitution in our study suggests a nontrivial elevation of cardiovascular risk on follow-up, and one similar to what has in fact been reported for SHS exposure (Law and Wald 2003).

**REFERENCES**


Holguin F, Tellez-Rojo MM, Lazo M, Mannino D, Schwartz J,


