Monitoring Low Benzene Exposure: Comparative Evaluation of Urinary Biomarkers, Influence of Cigarette Smoking, and Genetic Polymorphisms

Silvia Fustinoni,1 Dario Consonni,1 Laura Campo,1 Marina Buratti,1 Antonio Colombi,1 Angela C. Pesatori,1 Matteo Bonzini,1 Pier A. Bertazzi,1 Vito Foà,2 Seymour Garte,2 Peter B. Farmer,3 Leonard S. Levy,4 Mauro Pala,5 Federico Valerio,5 Vincenzo Fontana,5 Arianna Desideri,2 and Domenico F. Merlo5

1Department of Occupational and Environmental Health, University of Milan and Fondazione Ospedale Maggiore Policlinico, Mangiagalli e Regina Elena, Milan, Italy; 2School of Public Health, University of Medicine and Dentistry of New Jersey, Piscataway, New Jersey; 3Cancer Biomarkers and Prevention Group, Biocentre and Medical Research Council, Institute for Environmental and Health, University of Leicester, Leicester, United Kingdom; and 5Environmental Epidemiology and Biostatistics, Department of Cancer Epidemiology and Epidemiology, National Cancer Research Institute, Genoa, Italy

Abstract

Benzene is a human carcinogen and an ubiquitous environmental pollutant. Identification of specific and sensitive biological markers is critical for the definition of exposure to low benzene level and the evaluation of the health risk posed by this exposure. This investigation compared urinary trans,trans-muconic acid (t,t-MA), S-phenylmercuric acid, and benzene (U-benzene) as biomarkers to assess benzene exposure and evaluated the influence of smoking and the genetic polymorphisms CYP2E1 (RsaI and/or Dral) and NADPH quinone oxidoreductase-I on these indices. Gas station attendants, urban policemen, bus drivers, and two groups of controls were studied (415 subjects). Median benzene exposure was 61, 22, 9 and 6 μg/m³, respectively, with higher levels in workers than in controls. U-benzene, but not t,t-MA and S-phenylmercuric acid, showed an exposure-related increase. All the biomarkers were strongly influenced by cigarette smoking, with values up to 8-fold higher in smokers compared with nonsmokers. Significant correlations of the biomarkers with each other and with urinary cotinine were found. A possible influence of genetic polymorphism of CYP2E1 (RsaI and/or Dral) on t,t-MA and U-benzene in subjects with a variant allele was found. Multiple linear regression analysis correlated the urinary markers with exposure, smoking status, and CYP2E1 (RsaI; R² up to 0.55 for U-benzene). In conclusion, in the range of investigated benzene levels (<478 μg/m³ or <0.15 ppm), smoking may be regarded as the major source of benzene intake; among the study indices, U-benzene is the marker of choice for biomonitoring low-level occupational and environmental benzene exposure. (Cancer Epidemiol Biomarkers Prev 2005;14(9):2237–44)

Introduction

Benzene, a known human carcinogen (group 1 IARC; ref. 1), is a major chemical widely used all over the world in the production of monomers for the polymer industry and in the synthesis of intermediates. In some countries, benzene is still used as a solvent (2). As a consequence of these production activities, it is found as an airborne pollutant in industrial environments. Benzene is also distributed in the general environment by vehicles due to both fuel evaporation and gas-fueled engine emissions (3). Benzene is originally present in fuel (<1% v/v in the United States and European Union) and is additionally produced by engines because of incomplete combustion of the organic components of gas. Moreover, benzene is a component of mainstream and side-stream cigarette smoke (4, 5). Due to its multiple sources, benzene occupational or environmental exposure may concern the major part of the population.

In the last decades in developed countries, airborne benzene in traditionally polluted working settings has progressively decreased as a consequence of preventive actions. On the other hand, benzene concentration in living environments, particularly in large cities, has reached levels that cause concern for public health. Consequently, benzene exposure in working and living environments is often very similar, with concentrations in the 1 to 1,000 μg/m³ range (<0.001-0.312 ppm).

For the definition of exposure to low levels of benzene as well as for the evaluation of health risks posed by this exposure, the identification of suitable, specific, and sensitive biological markers is needed. This need is further supported by recent evidence that indicates that benzene causes hematotoxicity at occupational levels below 1 ppm (6).

Inhaled benzene is readily absorbed into the blood at 40% to 70% of airborne doses by passive diffusion through alveolar capillary membranes. Major elimination occurs via the same mechanism with exhaled air. Once in the body, benzene is oxidized by cytochrome P450 enzymes (CYP2E1) to a reactive intermediate benzene oxide-oxepine. This highly reactive species is further metabolized through three different pathways. The predominant one leads to phenol via a nonenzymatic rearrangement. Phenol may be excreted in urine as sulfate or glucuronate derivatives (80-90% of the absorbed dose) or may be oxidized, via cytochrome P450, to 1,4- and 1,2-benzenediol, and this may be further oxidized to p- and o-benzoquinone. The quinones may be back-reduced to the original diols via NADPH quinone oxidoreductase-I (NQO1). The second pathway leads to benzene 1,2-dihydrodiol via...

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Requests for reprints: Silvia Fustinoni, Department of Occupational and Environmental Health, University of Milan and Instituti Clinici di Perfezionamento, Via S. Barnaba, 8, 20122 Milan, Italy. Phone: 39-2-503-20116; Fax: 39-2-503-20110. E-mail: silvia.fustinoni@unimi.it

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epoxide hydrolase, which may be oxidized to trans,trans-
muconic aldehyde and to trans,trans-muconic acid (t,t-MA),
which is excreted in urine (3-18% of the adsorbed dose). The
minor pathway leads to pre-phenyl mercapturic acid, after
conjugation with glutathione via glutathione S-transferase,
and finally to S-phenylmercapturic acid (S-PMA), which is
excreted in urine (<1% of the absorbed dose; reviewed in
ref. 7). Nonmetabolized benzene may be also excreted in urine
(U-benzene) after passive diffusion from blood to urine
through the kidney glomerular tuft (<0.1% of the absorbed
dose; ref. 8).

For prevention of risk arising from exposure to benzene, an
occupational limit value of 3,200 μg/m³ (1 ppm) has been
adopted by the European Union (9), whereas a threshold limit
value of 1,600 μg/m³ (0.5 ppm) as maximal time-weighted
average during an 8-hour shift is recommended by the
American Conference of Governmental Industrial Hygienists
(10). As biological exposure indices, the use of t,t-MA and
S-PMA in urine samples collected at the end of work shift are
indicated. Blood benzene is also suggested as a nonquantita-
tive, but specific, index. In addition to these indices, some
authors suggested U-benzene as a sensitive and specific
marker for the biological monitoring of benzene exposure
(8, 11-15). Although the cited biomarkers have proven to be
suitable for assessment of exposure to airborne benzene
(S-PMA, and U-benzene to detect occupational and environ-
mental low benzene exposure and to determine how smoking
and the suburban areas surrounding them were investigated.

Materials and Methods

Study Population. The study was carried out from October
1999 to June 2000 on subjects exposed to benzene as a pollutant
of the general and/or occupational environment of urban areas
within or near two large cities in northern Italy, Milan, and
Genoa. In the Milan area, the investigated subjects were
recruited among gas station attendants (n = 78), urban traffic
policemen (n = 77), and subjects working in offices and
hospital facilities located downtown, designated as Milan
referents (n = 58). In the Genoa area, subjects were recruited
among municipal bus drivers (n = 153) and subjects working
as clerks and researchers at the National Institute for Cancer
Research in the urban environment and designated as Genoa
referents (n = 49). Referent (nonexposed) subjects were
matched by gender, age, and smoking habits. Workers
received information about the aim of the research, and
written informed consent was obtained. Detailed information
about smoking habits, lifestyle, medical history, and occupa-
tional activity of the investigated subjects was obtained by a
self-administered questionnaire.

Personal Benzene Exposure

Airborne Benzene. Airborne benzene was collected by
a passive sampler (stainless steel tube, 9 mm internal diameter
× 90 mm length) containing Chromosorb 106 and equipped
with a diffusion chamber that was worn by the investigated
subjects near the breathing zone during part of the work shift
(typically from 8:00 a.m. to 2:00 p.m.; ref. 16). At the end of
the monitored period, the passive sampler was closed with a
brass cap and nut, equipped with a polyperfluoroethylene
ferule, and kept at −20°C until analysis. Benzene in samples
was determined by thermal desorption followed by gas
chromatography/flame ionization detector analysis. The limit of
detection for airborne benzene was 6 μg/m³ (0.002 ppm).

Biological Monitoring

Specimen Collection. Urine spot samples were collected twice
for each subject, once at the beginning and the other at the end
of the monitored period. Specimens were partitioned in
plastic tubes for cotinine (pre-monitoring sample, T0), t,t-MA
(pre-monitoring and post-monitoring samples, T0 and T1),
and S-PMA [post-monitoring sample, T2; 6 mol/L HCl/1 mL
urine (12.5 μL) was added as a preserving agent]. For U-
benzene, a 7-μL aliquot was poured into a precleaned 8-μL
glass vial, promptly closed with a rubber lid with a polypyr-
fluoroethylene lining, and crimped with an aluminum seal
(pre-monitoring and post-monitoring samples, T0 and T1,
collected only for the Milan subjects). All samples were
coded, frozen at −20°C, and delivered to the various
laboratories, where analyses were done without knowledge of
their origin.

Urinary t,t-MA. Determination of urinary t,t-MA was carried
out by pre-purification of urine with solid-phase extraction
using a strong anion exchange column (300 mg, Supeleo,
Milan, Italy) followed by high-performance liquid chromatog-
raphy and UV detection according to a published procedure
(17). The detection limit of the procedure was 10 μg/L.

Urinary S-PMA. Determination of urinary S-PMA was based
on an immunoassay technique according to a previously
published procedure (18). The immunoassay plate-based kit
and reagents were from AB Biomonitoring Ltd. (Cardiff,
Wales, United Kingdom). The detection limit of the procedure
was 0.2 μg/L.

U-benzene. Determination of U-benzene was done by
headspace solid-phase microextraction followed by gas chro-
matography/mass spectrometry analysis according to a
published method (19) with some modifications. Briefly, 0.5
mL urine was poured in a 2-mL autosampler vial containing
300 mg NaCl. The internal standard solution of benzene-d6
(1 μL) in methanol (0.475 μg/L) was added, and the vial was
immediately closed with a screw-holed cap equipped with a
silicone-polyperfluoroethylene gasket. Benzene was sampled
from the urine headspace by the solid-phase microextraction
technique using a PDMS fiber. Sampling was operated at room
temperature with a Varian CX8200 autosampler. Analyte
separation was done by gas chromatography using a BD1
column (60 m length, 0.25 mm internal diameter, 1 μm film
thickness). Quantification was done using a mass spectrometry
detector operating in the electron impact mode. The detection
limit of the procedure was 15 ng/L.

U-cotinine. Determination of urinary cotinine was carried
out by high-performance liquid chromatography and UV
detection according to a published procedure (20). The
detection limit of the procedure was 50 μg/L.

Genetic Polymorphisms. For analysis of CYP2E1, samples
were amplified using the following primers: 5′-CCAGTC-
GAGTCTACATTGTCA and 3′-TTATTTTGTCTCTAAT-
CTGG. PCR was done for 30 cycles with denaturing at 95°C
for 1 minute, annealing at 55°C for 1 minute, and extension at
72°C for 1 minute. PCR products are digested with excess RsI or
DraI less enzyme.

For analysis of the NQO1 RFLP, DNA samples were
amplified in a total reaction volume of 50 μL containing
1.2 mmol/L deoxynucleotide triphosphate, 1.2 mmol/L oligo-
nucleotide primers, and 2.5 units Taq polymerase (Amplitaq,
Perkin-Elmer, Boston, MA) using the following primers: 5′-
GAGACGCTAGCTCTGAACTGAT and 5′-GAGTCTACATTGTCA and 3′-
V for 1 minute. PCR products are digested with excess RsI and
DraI less enzyme.

For analysis of the NQO1 RFLP, DNA samples were
amplified in a total reaction volume of 50 μL containing
1.2 mmol/L deoxynucleotide triphosphate, 1.2 mmol/L oligo-
nucleotide primers, and 2.5 units Taq polymerase (Amplitaq,
Perkin-Elmer, Boston, MA) using the following primers: 5′-
GAGACGCTAGCTCTGAACTGAT and 5′-GAGTCTACATTGTCA and 3′-
V for 1 minute. PCR products are digested with excess RsI and
DraI less enzyme.
Both cities All jobs 415 352 63 38.5

conducted parallel analyses with parametric methods on log10-detection limit was assigned to measurements below analytic
corresponding to one-half of the
comparisons among the occupational groups and between pre-
benzene exposure and the urinary biomarkers by making
agarose and visualized by ethidium bromide staining.

Multiple linear regression analyses were done on log 10-transformed variables (\(\log_{10}\) transformed variables). In every model we included, as dependent variable, the different urinary biomarkers and, as predictors, the exposure variables (airborne benzene and current exposure to cigarette smoke, measured as U-cotinine) and the CYP2E1 (RsaI) polymorphism (0 = wild-type, 1 = at least one mutant allele), which had been found to be associated with the
allele), which had been found to be associated with the
statistically significant, they were omitted from the final model

results

Statistical Analyses. We assessed the relationship of benzene exposure and the urinary biomarkers by making comparisons among the occupational groups and between pre- and post-shift samples and by using correlation/regression
techniques. A value corresponding to one-half of the
detection limit was assigned to measurements below analytic
corresponding to one-half of the

Statistical Analyses. We assessed the relationship of benzene exposure and the urinary biomarkers by making comparisons among the occupational groups and between pre- and post-shift samples and by using correlation/regression
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detection limit was assigned to measurements below analytic
corresponding to one-half of the

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techniques. A value corresponding to one-half of the
detection limit was assigned to measurements below analytic
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detection limit was assigned to measurements below analytic
corresponding to one-half of the
detection limit was assigned to measurements below analytic

93°C for 1 minute, annealing at 65°C for 1 minute, and extension at 72°C for 1 minute. PCR products were digested with excess

Results

Study Population. Selected characteristics of study subjects are reported in Table 1. Comparing Genoa and Milan subjects, we noticed that the former were almost entirely males, whereas the latter had a higher prevalence of females (overall, ~30%), mainly distributed in referents and traffic policemen. Self-reported smoking prevalence was similar across job titles and cities, with an overall 35% of cigarette smokers and a mean daily consumption of 16 cigarettes. The
good correlation coefficient found between self-reported daily cigarette consumption and the level of urinary cotinine (\(r = 0.291\)) proves the reliability of smoking level collected thought

Personal Benzene Exposure and Biological Monitoring. In Table 2, data on personal exposure to airborne benzene, as time-weighted average value, excretion of \(t\)-MA (\(T_0\) and \(T_1\)), S-PMA, and U-benzene (\(T_0\) and \(T_1\)), in subjects divided according to city, job title, and smoking habits are reported. Using parametric statistics, higher personal exposures were found in gas station attendants, followed by traffic policemen and bus drivers, with comparable levels, and finally by the two

Table 2. Summary of biological markers of benzene exposure in the investigated subjects divided according to city, job
titles, and smoking habits

<table>
<thead>
<tr>
<th>Location</th>
<th>Jobs</th>
<th>Air benzene (μg/m³), median (min-max)</th>
<th>(t)-MA (T_0) (μg/L), median (min-max)</th>
<th>(t)-MA (T_1) (μg/L), median (min-max)</th>
<th>S-PMA (T_1) (μg/L), median (min-max)</th>
<th>U-benzene (T_0) (ng/L), median (min-max)</th>
<th>U-benzene (T_1) (ng/L), median (min-max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Genoa</td>
<td>Referents</td>
<td>Nonsmokers</td>
<td>72 (&lt;10-398)</td>
<td>51 (&lt;10-181)</td>
<td>9.0 (0.2-182.2)</td>
<td>Not determined</td>
<td>Not determined</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Smokers(^1)</td>
<td>190 (519-1,850)</td>
<td>195 (&lt;10-444)</td>
<td>13.7 (3.0-19.9)</td>
<td>0/13</td>
<td>0/13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bus drivers</td>
<td>85 (&lt;10-2,014)</td>
<td>57 (&lt;10-536)</td>
<td>5.6 (0.2-13.3)</td>
<td>0/13</td>
<td>0/13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nonsmokers</td>
<td>136 (&lt;10-600)</td>
<td>174 (&lt;10-695)</td>
<td>9.3 (0.2-65.9)</td>
<td>Not determined</td>
<td>Not determined</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Smokers(^1)</td>
<td>35 (&lt;10-576)</td>
<td>33 (&lt;10-1,089)</td>
<td>4.1 (0.2-12.5)</td>
<td>0/13</td>
<td>0/13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Traffic policemen</td>
<td>35 (&lt;10-576)</td>
<td>33 (&lt;10-1,089)</td>
<td>4.1 (0.2-12.5)</td>
<td>0/13</td>
<td>0/13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nonsmokers</td>
<td>9/23</td>
<td>7/23</td>
<td>8.0 (0.2-13.9)</td>
<td>0/13</td>
<td>0/13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Smokers(^1)</td>
<td>4/23</td>
<td>4/23</td>
<td>8.0 (0.2-13.9)</td>
<td>0/13</td>
<td>0/13</td>
</tr>
<tr>
<td>Milan</td>
<td>Referents</td>
<td>Nonsmokers</td>
<td>51 (&lt;10-246)</td>
<td>51 (&lt;10-270)</td>
<td>0/13</td>
<td>0/13</td>
<td>0/13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Smokers(^1)</td>
<td>35 (&lt;10-576)</td>
<td>73 (&lt;10-207)</td>
<td>0/13</td>
<td>0/13</td>
<td>0/13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gas station attendants</td>
<td>22 (&lt;9-316)</td>
<td>82 (&lt;10-416)</td>
<td>5.3 (0.2-13.8)</td>
<td>0/13</td>
<td>0/13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nonsmokers</td>
<td>86 (&lt;10-1,400)</td>
<td>84/9/49</td>
<td>9.1 (2.4-13.8)</td>
<td>0/13</td>
<td>0/13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Smokers(^1)</td>
<td>222 (&lt;10-1,400)</td>
<td>213 (52-909)</td>
<td>9.1 (2.4-13.8)</td>
<td>0/13</td>
<td>0/13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nonsmokers</td>
<td>35 (&lt;10-672)</td>
<td>49 (&lt;10-581)</td>
<td>5.8 (0.2-10.9)</td>
<td>0/13</td>
<td>0/13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Smokers(^1)</td>
<td>64/6/46</td>
<td>144 (15-321)</td>
<td>7.5 (0.2-24.8)</td>
<td>0/13</td>
<td>0/13</td>
</tr>
</tbody>
</table>

\(^1\)Observations below the detection limit versus total observation.

\(^2\)Gas station attendants higher than bus drivers and traffic policemen, higher than controls (\(P < 0.01\)).

\(^3\)Smokers higher than nonsmokers for all the biomarkers (\(P < 0.001\)); statistical analysis was done with \(t\) test for independent samples on \(log_{10}\)-transformed variables.

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found in smokers; as expected, such correlations were not found in nonsmokers. Spearman’s correlation analysis between environmental and biological markers fully confirms these results.

Genetic Polymorphisms. The observed genotypes agree with allele frequencies reported previously for other European populations (21). No differences in the frequencies of genotypes among the groups with different job titles were found ($\chi^2$ test was used for comparison). Based on this observation, the total study group ($n = 415$) was used for analyses of the effects of polymorphic genotypes on exposure biomarkers. The results of $t$ test comparison, reported in Table 4, showed higher median levels of $t,t$-MA $T_0$ but not of $t,t$-MA $T_1$, in subjects with at least one variant allele in CYP2E1 (RsaI) or CYP2E1 (DraI). Furthermore, a lower median level of U-benzene $T_1$ in subjects with one variant allele in CYP2E1 (RsaI) was found. A similar, but not significant, difference was found for U-benzene $T_0$. No influence of genetic polymorphism of NQO1 or of the combination of CYP2E1 (RsaI) and CYP2E1 (DraI) polymorphisms on urinary biomarkers was observed. When the Kruskal-Wallis test was applied to untransformed data for group comparison, slight differences with the previous analysis were noticed. In particular, higher median levels of $t,t$-MA $T_0$ but not of $t,t$-MA $T_1$ in subjects with at least one variant allele in CYP2E1 (DraI; $P = 0.03$) but not in CYP2E1 (RsaI; $P = 0.07$) was observed. Furthermore, a lower median level of both U-benzene $T_0$ and U-benzene $T_1$ in subjects with one variant allele in CYP2E1 (RsaI; $P < 0.01$ and 0.03) was found.

Multiple Linear Regression Analysis. The adjusted multiple regression analyses (Table 5) substantially confirmed the findings of univariate analyses. We observed significant relationships between each of the urinary biomarkers and smoking (measured as U-cotinine); instead, after adjustment for smoking and CYP2E1 (RsaI) polymorphism, only U-benzene was significantly positively related to airborne benzene; this variable alone explained ~20% of the variability in U-benzene. Accordingly, the adjusted $R^2$ for the models containing U-benzene as the dependent variable were 0.55 and 0.41 for pre-shift and post-shift measurements, respectively, much higher than those obtained when the other biomarkers were analyzed (0.10-0.20). We found a significant increase of $t,t$-MA for U-benzene $T_0$ compared with nonsmokers, in both application of nonparametric statistics confirms these results.
In the last decade, several studies were carried out to evaluate NQO1 CYP2E1 (both pre-shift and post-shift). This study reflects a trend toward lower levels in comparison with previous publications on traffic policemen, gas station attendants, and the general population working within or near two large cities of northern Italy, Genoa, and Milan were investigated through environmental and biological monitoring.

Comparing personal exposure to benzene in the different job titles, we observed that gas station attendants showed the highest level (median, 61 μg/m³ or 0.017 ppm) followed by traffic policemen (21 μg/m³ or 0.007 ppm), with comparable exposure, and finally by the two groups of referents (9 and 6 μg/m³ or 0.003 and 0.002 ppm) with the lowest concentrations (Table 2). This exposure rank is in line with what was expected based on previous experience, although the concentrations measured in this study reflect a trend toward lower levels in comparison with the past (25-27, 31, 32). Such improvement in air quality may be due to at least three major initiatives undertaken by the Italian government in the last years: (a) the lowering of the maximum permissible percentage of benzene in gasoline, (b) the economic incentive for purchasing new cars equipped with catalytic converters, and (c) the aspiration system applied to the nozzle of the gasoline pump for vapor recovery (36, 37).

Considering the workers with the highest exposure levels (i.e., gas station attendants), median and maximum benzene levels of 61 and 478 μg/m³ (0.019 and 0.15 ppm) are, respectively, 52- and 7-fold lower than the European Union occupational limit value of 3,200 μg/m³ (1 ppm; ref. 9) recently adopted in Italy but also lower than the limit value recommended or stated by industrial hygiene associations or governmental authorities (10). On the contrary, exposure to benzene in referents, with median and maximum levels up to 9 and 175 μg/m³ (0.003 and 0.05 ppm), is about equal to and up to 12-fold higher than the European Union air quality standard of 10 μg/m³ (0.003 ppm; ref. 38).

Considering urinary t,MA as a biomarker of occupational exposure to benzene, we found that in the different job titles there were no differences related to personal exposure or correlation with airborne benzene (Tables 2 and 3). This finding is consistent with previous studies, as reviewed by Scherer et al. (39) and Dor et al. (40). Moreover, recent publications on traffic policemen, gas station attendants, and

### Table 3. Pearson’s correlations between environmental and biological markers and between biomarkers themselves in all investigated subjects, nonsmokers, and smokers

<table>
<thead>
<tr>
<th></th>
<th>t,MA T₀</th>
<th>t,MA T₁</th>
<th>S-MA</th>
<th>U-benzene T₀</th>
<th>U-benzene T₁</th>
<th>U-cotinine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air benzene</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All subjects</td>
<td>0.05 (411)</td>
<td>0.10² (412)</td>
<td>0.04 (370)</td>
<td>0.41¹ (204)</td>
<td>0.38¹ (210)</td>
<td>0.05 (412)</td>
</tr>
<tr>
<td>Nonsmokers</td>
<td>0.00 (268)</td>
<td>0.09 (269)</td>
<td>0.04 (242)</td>
<td>0.56¹ (125)</td>
<td>0.53³ (128)</td>
<td>0.04 (269)</td>
</tr>
<tr>
<td>Smokers</td>
<td>0.09 (143)</td>
<td>0.06 (143)</td>
<td>-0.03 (128)</td>
<td>0.30¹ (79)</td>
<td>0.23² (82)</td>
<td>-0.07 (143)</td>
</tr>
<tr>
<td>t,MA T₀</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All subjects</td>
<td>0.55³ (412)</td>
<td>0.27¹ (369)</td>
<td>0.24¹ (241)</td>
<td>0.10 (125)</td>
<td>0.03 (128)</td>
<td>-0.12 (269)</td>
</tr>
<tr>
<td>Nonsmokers</td>
<td>0.47¹ (269)</td>
<td>0.17 (128)</td>
<td>0.32¹ (76)</td>
<td>0.13 (82)</td>
<td>0.48¹ (143)</td>
<td></td>
</tr>
<tr>
<td>Smokers</td>
<td>0.60³ (143)</td>
<td>0.43¹ (370)</td>
<td>0.35¹ (203)</td>
<td>0.27¹ (210)</td>
<td>0.44³ (413)</td>
<td></td>
</tr>
<tr>
<td>t,MA T₁</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All subjects</td>
<td>0.34¹ (242)</td>
<td>0.08 (125)</td>
<td>0.04 (128)</td>
<td>0.02 (270)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nonsmokers</td>
<td>0.47¹ (128)</td>
<td>0.40¹ (78)</td>
<td>0.28 (82)</td>
<td>0.60³ (143)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smokers</td>
<td>0.30³ (72)</td>
<td>0.54¹ (77)</td>
<td>0.38³ (128)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S-MA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All subjects</td>
<td>0.39³ (189)</td>
<td>0.40¹ (197)</td>
<td>0.33³ (370)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nonsmokers</td>
<td>0.25¹ (117)</td>
<td>0.17 (120)</td>
<td>0.13 (242)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smokers</td>
<td>0.30³ (72)</td>
<td>0.54¹ (77)</td>
<td>0.38³ (128)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U-benzene T₀</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All subjects</td>
<td>0.71¹ (201)</td>
<td>0.64³ (203)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nonsmokers</td>
<td>0.62¹ (124)</td>
<td>0.00 (125)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smokers</td>
<td>0.54¹ (77)</td>
<td>0.47³ (78)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U-benzene T₁</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All subjects</td>
<td>0.53³ (210)</td>
<td>0.07 (128)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nonsmokers</td>
<td>0.07 (128)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smokers</td>
<td>0.33³ (82)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*P < 0.05.

### Table 4. Biomarkers of exposure in all investigated subjects divided according to different polymorphic genotypes

<table>
<thead>
<tr>
<th>Polymorphic genotype/genotype subgroups</th>
<th>t,MA T₀ μg/L, median (min-max), n</th>
<th>t,MA T₁ μg/L, median (min-max), n</th>
<th>S-MA μg/L, median (min-max), n</th>
<th>U-benzene T₀ ng/L, median (min-max), n</th>
<th>U-benzene T₁ ng/L, median (min-max), n</th>
</tr>
</thead>
<tbody>
<tr>
<td>CYP2E1 (Ras1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wild-type</td>
<td>76 (&lt;10-1,850), 382</td>
<td>79 (&lt;10-1,089), 382</td>
<td>67 (0.2-182.2), 340</td>
<td>438 (77-6,430), 189</td>
<td>283 (15-5,111), 194</td>
</tr>
<tr>
<td>ht variant</td>
<td>118 (&lt;10-2,014), 27</td>
<td>98 (&lt;10-2,866), 28</td>
<td>56 (0.2-16.0), 28</td>
<td>264 (72-6,235), 13</td>
<td>149 (54-1,70), 14</td>
</tr>
<tr>
<td>P*</td>
<td>0.05</td>
<td>0.14</td>
<td>0.23</td>
<td>0.09</td>
<td>0.03</td>
</tr>
<tr>
<td>CYP2E1 (Dra1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wild-type</td>
<td>74 (&lt;10-1,850), 349</td>
<td>77 (&lt;10-1,089), 349</td>
<td>66 (0.2-182.2), 308</td>
<td>450 (77-6,430), 173</td>
<td>273 (25-5,111), 177</td>
</tr>
<tr>
<td>ht + ho variant P*</td>
<td>0.02</td>
<td>0.69</td>
<td>0.75</td>
<td>0.63</td>
<td>0.46</td>
</tr>
<tr>
<td>NQO1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wild-type</td>
<td>87 (&lt;10-2,014), 238</td>
<td>84 (&lt;10-1,089), 239</td>
<td>66 (0.2-182.2), 212</td>
<td>421 (72-6,430), 115</td>
<td>248 (25-4,246), 121</td>
</tr>
<tr>
<td>ht + ho variant P*</td>
<td>0.40</td>
<td>0.40</td>
<td>0.78</td>
<td>0.69</td>
<td>0.96</td>
</tr>
</tbody>
</table>

NOTE: Comparison between genotype subgroups was done by t test for independent samples.

*P for comparison with t test for independent samples on log₁₀-transformed variables between the genotype subgroups.
Table 5. Evaluation of airborne benzene exposure, smoking status (as urinary cotinine), and CYP2E1 (Rs1) genotype on urinary biomarkers according to linear multiple regression analysis: \( \log_{10}(\text{U-Biomarker}) = \text{constant} + \log_{10}(\text{BenzenAir}) \times t_{f, t} + \log_{10}(\text{U-cotinine}) \times t_{f, 2} + \text{CYP2E1 (Rs1)} \times t_{f, 3} \)

<table>
<thead>
<tr>
<th></th>
<th>( t_{f, MA} T_0 )</th>
<th>( t_{f, MA} T_1 )</th>
<th>( S\text{-PMA} )</th>
<th>( \text{U-benzene} T_0 )</th>
<th>( \text{U-benzene} T_1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \beta )</td>
<td>( R^2 ), P</td>
<td>( R^2 ), P</td>
<td>( R^2 ), P</td>
<td>( R^2 ), P</td>
<td>( R^2 ), P</td>
</tr>
<tr>
<td>Constant</td>
<td>1.27 (0.11)</td>
<td>1.07 (0.10)</td>
<td>0.28 (0.09)</td>
<td>1.48 (0.09)</td>
<td>1.35 (0.11)</td>
</tr>
<tr>
<td>( P ) adj</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Benzene Air</td>
<td>0.05 (0.06)</td>
<td>0.09 (0.05)</td>
<td>0.01 (0.05)</td>
<td>0.34 (0.05)</td>
<td>0.36 (0.05)</td>
</tr>
<tr>
<td>( P ) adj</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>U-cotinine</td>
<td>0.24 (0.04)</td>
<td>0.32 (0.03)</td>
<td>0.21 (0.03)</td>
<td>0.43 (0.01)</td>
<td>0.41 (0.03)</td>
</tr>
<tr>
<td>( P ) adj</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>CYP2E1 (Rs1)</td>
<td>0.29 (0.11)</td>
<td>-0.07 (0.10)</td>
<td>-0.07 (0.09)</td>
<td>-0.21 (0.10)</td>
<td>-0.25 (0.11)</td>
</tr>
<tr>
<td>( P ) adj</td>
<td>0.02, 0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>0.02, 0.03</td>
<td>0.03, 0.02</td>
</tr>
<tr>
<td>Whole model</td>
<td>0.10, &lt;0.01</td>
<td>0.20, &lt;0.01</td>
<td>0.10, &lt;0.01</td>
<td>0.55, &lt;0.01</td>
<td>0.41, &lt;0.01</td>
</tr>
<tr>
<td>( R^2 ) adj</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

NOTE: Values of constant and \( \beta \) coefficient, with \( P \), partial \( R^2 \) and significance (\( P \)) for each term of the equation, are given. Adjusted \( R^2 \) \((R^2_{\text{adj}})\) and the significance (\( P \)) for the whole model are reported in the last row. Statistical analysis was done on log_{10}-transformed variables.

bus drivers confirmed the lack of differences between workers and the general population in \( t_{f, MA} \) excretion (13, 28, 30). Indeed, a benzene threshold, ranging from 800 to 3,200 \( \mu g/m^3 \) (0.25-1 ppm), below which \( t_{f, MA} \) may not be a useful biomarker for exposure to benzene, was suggested (11, 41, 42). In the present study, both the median and the highest benzene exposure were well below these values.

In addition to smoking and genetic polymorphisms (discussed later), the preserving agent sorbic acid and its salts (sorbates), contained in a large variety of food and drinks, may have contributed to the observed level of urinary \( t_{f, MA} \) (43-45). According to Ruppert et al. (43), as much as 50% of \( t_{f, MA} \) excreted in nonsmoking subjects and up to 25% in smoking, nonoccupationally exposed subjects may be ascribed to the contribution of these molecules. Because we did not collect information on food and drink intake in the study subjects, the contribution of sorbic acid and its salts in the excretion of \( t_{f, MA} \) could not be properly evaluated.

\( S\text{-PMA} \) is generally considered a very specific biomarker of benzene, successfully applied to distinguish exposed and nonexposed subjects (35, 41, 42, 46-49) and correlated with personal exposure starting from low concentrations [reviewed by Dor et al. (40)]. In the present study, \( S\text{-PMA} \) was also a poor biomarker of occupational exposure to benzene. This is consistent with a recent field study on traffic policemen in which \( S\text{-PMA} \) failed to distinguish exposed from unexposed subjects (28). Overall, available evidence does not allow setting an unequivocal threshold above which this index may be applied: benzene concentrations ranging from 64 to 960 \( \mu g/m^3 \) (0.02-0.3 ppm) were above which this index may be applied: benzene concentrations ranging from 64 to 960 \( \mu g/m^3 \) (0.02-0.3 ppm) were
only environmental benzene) was estimated to be 4.7 in controls, 3.5 in bus drivers or traffic policemen, and 2.4 in gas station attendants. These values are in good agreement with the ratio obtained in this study between urinary biomarkers detected in smokers and nonsmokers (1.5-3.8 for t,t-M, 1.5-2.0 for S-PMA, and 2.5-8.0 for U-benzene; Table 2) as well as those reported in previous investigations (42, 43, 45, 51). Based on these calculations, we would predict a daily benzene intake higher in smoking referents (194 ng/d from inhalation of polluted air + 720 µg/d from cigarettes = 914 µg/d) than in nonsmoking gas station attendants (526 µg/d). This estimate is consistent with the levels of U-benzene measured in smoking referents (560 and 351 ng/L in T₀ and T₁ samples) compared with nonsmoking gas station attendants (459 and 342 ng/L in T₀ and T₁ samples).

U-cotinine significantly correlated with t,t-M, S-PMA, and U-benzene in all subjects and in smokers. The correlations with personal exposure were significant only for U-benzene, not for t,t-M and S-PMA. From the linear regression of U-benzene T₁ versus air benzene (all subjects), it was calculated that an exposure of 320 µg/m³ (0.1 ppm) corresponds to a U-benzene excretion of 828 ng/L. This value agrees with those reported previously (13, 14). The correlations between biomarkers were generally higher in smokers compared with nonsmokers. These observations further support the relevance of additional benzene exposure due to cigarette smoking.

Rothman et al. have reported evidence of a genetic basis for human susceptibility to benzene-related disease (53). They found a higher probability of “benzene poisoning” (hematotoxicity) in heavily exposed Chinese workers having a rapid fractional excretion of chlorzoxazone (phenotype of CYP2E1) and two copies of the NQO1 600C–T mutation. Some evidences of the influence of genetic polymorphism in the production of benzene metabolites were also reported (23, 51, 54, 55). The result of our study suggests, for the first time, a role of genetic polymorphisms on the variability of the investigated biomarkers in heavy exposure (Table 4). The study population is large enough to allow for the detection of a small effect in a limited number of individuals as expected based on the mutation frequencies. These two polymorphisms in CYP2E1 have not been found to have a significant effect on benzene toxicity (53, 54) or CYP2E1 phenotype (56), although other studies have indicated a role for CYP2E1 genotype in benzene toxicity, gene expression, and disease risk (57-59). Our result on the effect of the CYP2E1 RFLP needs to be confirmed, as only t,t-M T₀ and U-benzene T₁ were significantly modified, U-benzene T₁ showed a trend toward decrease, whereas t,t-M T₁ was not influenced by the polymorphisms of CYP2E1.

Multiple linear regression analysis (Table 5) summarizes how the influence of genetic polymorphism on the variability of the investigated biomarkers seems to be limited in comparison with other factors: in fact, for U-benzene T₀ only 2% could be explained by genetic polymorphism of CYP2E1, whereas as much as 22% could be explained by personal exposure and 45% by smoking.

In conclusion, at the environmental levels of benzene exposure investigated, smoking plays a major role in individual benzene uptake. The comparison of t,t-M, S-PMA, and U-benzene as biomarkers of benzene exposure shows that U-benzene is performing best and may be applied for biological monitoring purposes starting from airborne benzene levels as low as 6 µg/m³ (0.002 ppm).

Acknowledgments

We thank the subjects who volunteered in the study and CONCAWE, the Oil Companies’ European Organization for Environment, Health, and Safety, for their support.

References

Monitoring Low Benzene Exposure by Urinary Biomarkers


Monitoring Low Benzene Exposure: Comparative Evaluation of Urinary Biomarkers, Influence of Cigarette Smoking, and Genetic Polymorphisms

Silvia Fustinoni, Dario Consonni, Laura Campo, et al.


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