Chromosomal Aberrations in Cord Blood Are Associated with Prenatal Exposure to Carcinogenic Polycyclic Aromatic Hydrocarbons

Kirsti A. Bocskay,1 Deliang Tang,1 Manuela A. Orjuela,1,2 Xinhua Liu,3 Dorothy P. Warburton,5,6 and Frederica P. Perera4

Departments of Environmental Health Sciences, 2Pediatrics, 3Biostatistics, and 4Columbia Center for Children’s Environmental Health, Mailman School of Public Health and Departments of Genetics and Development and Pediatrics, Columbia University, New York, New York

Abstract

Molecular and traditional epidemiology studies have indicated a possible relationship between in utero environmental exposures and increased risk for childhood cancers, especially acute leukemias. Chromosomal aberrations have been associated with environmental exposures and cancer risk in adults. In order to more clearly define the association between prenatal exposures to carcinogenic polycyclic aromatic hydrocarbons (PAH) and chromosomal aberrations, chromosomal aberration frequencies were measured in a subset of 60 newborns from the Columbia Center for Children’s Environmental Health (CCCEH) Prospective Cohort Study. The subset was composed of African American and Dominican, nonsmoking mother-newborn pairs residing in low-income neighborhoods of New York City, who were exposed to varying levels of airborne PAHs. Prenatal exposure was assessed by questionnaire, personal air monitoring during the third trimester, and PAH-DNA adducts in umbilical cord blood. Chromosomal aberrations were measured in cord blood lymphocytes by fluorescence in situ hybridization. PAH-DNA adducts were not associated with chromosomal aberrations. However, airborne PAHs were significantly associated with stable aberration frequencies in cord blood (P < 0.01). Moreover, stable aberration frequencies were significantly higher among African American newborns compared with Dominican, despite no significant differences in PAH exposure. These results show for the first time an association between prenatal exposure to airborne carcinogenic PAHs and chromosomal aberrations in cord blood, suggesting that such prenatal exposures have the potential to cause cytogenetic damage that has been related to increased cancer risk in other populations. If confirmed, this finding may open new avenues for prevention.

Introduction

Several lines of evidence suggest fetal susceptibility to carcinogens and that in utero exposure to environmental pollutants can result in carcinogenic DNA-adducts, chromosomal aberrations, and increased risk of childhood cancer (1-4). The short latency period seen in pediatric leukemias suggests in utero initiation of cancer (5-7), as does the discovery of the diagnostic chromosomal aberrations, PML-RARA, CBFB-MYH11, TEL/AML, AML/ETO, and MLL gene fusions, in archived bloodspots of children who were diagnosed with acute lymphocytic leukemia or acute myelocytic leukemia months to years after birth (8-12). Comparison of PAH-DNA adducts and cotinine in cord and maternal blood suggests differential fetal sensitivity to PAH and tobacco smoke (13, 14). Heightened fetal susceptibility to these carcinogens could result from higher rates of cell proliferation and differentiation, greater absorption or retention of xenobiotics, and/or less efficient detoxification, DNA repair, or apoptotic mechanisms (15-19). Finally, although epidemiologic studies have been inconsistent with respect to childhood cancer (20-22), several studies have linked prenatal tobacco smoke and PAH exposure to increases or qualitative differences in biomarkers such as cotinine, carcinogen-DNA adducts, somatic mutations, and chromosomal aberrations (1, 2, 23, 24).

PAHs are pervasive environmental toxicants in ambient air resulting in large part from the incomplete combustion of fossil fuels. Multiple studies comparing genetic damage in persons living in polluted, industrialized urban areas with those living in less polluted, rural areas have found significantly increased levels of carcinogen-DNA and -protein adducts, sister chromatid exchanges, somatic mutation frequencies, and/or chromosomal aberrations in adults (13, 25-28).

Prospective cohort studies by the European Study Group on Cytogenetic Biomarkers and Health have validated chromosomal aberrations as a biomarker of cancer risk, especially for hematologic malignancies (29). Nested case-control studies in the Nordic and Italian cohorts showed that chromosomal aberrations are an intermediate step in the carcinogenic pathway and are independent of exposure status, substantiating the role of chromosomal aberrations in cancer and indicating that they reflect both exposure and susceptibility (29, 30). Chromosomal aberrations in adults have been widely studied in nonoccupational and occupational settings (28, 29, 31-33). However, only two studies have measured chromosomal aberrations by fluorescence in situ hybridization (FISH) to monitor the impact of in utero environmental exposures, and sample sizes have been small (≤ 40 subjects; refs. 1, 2, 34). The present study was intended to address this gap.
Materials and Methods

Study Population. The Columbia Center for Children’s Environmental Health (CCCEH) cohort study population is composed of more than 600 African American or Dominican mother-infant pairs, as previously described (14, 35). The subjects reside in low-income, predominantly minority neighborhoods in Northern Manhattan and the South Bronx. These urban areas are densely populated and subject to varying levels of environmental PAHs from transportation and stationary sources including motor vehicles, diesel bus depots, residential heating, waste incinerators, and environmental tobacco smoke (ETS). African American and Latino women, 18 to 35 years old, were recruited from New York Presbyterian Hospital, Harlem Hospital, or satellite clinics at 16 to 20 weeks of pregnancy during their prenatal visit. Enrollment was carried out so that the sample population under study was uniformly distributed across the urban area in order to capture variation in environmental exposures. Exclusion criteria included active smoking, illicit drug use, diagnosis of diabetes (including gestational diabetes) or HIV as determined by responses to the eligibility screening questionnaire, or an initial prenatal visit after 20 weeks of gestation. Participating women signed a consent form approved by the institutional review board at Columbia University. All samples and data were coded and kept in locked storage units to protect confidentiality of study subjects. Women were compensated for their participation in each phase of the parent study. To be fully enrolled into the parent prospective cohort study, women had to have completed prenatal air monitoring.

Sixty newborns were randomly chosen for chromosomal aberration analysis. Demographic data for the subset and total population are presented in Table 1. The subset of newborns who underwent chromosomal aberration analysis did not differ from the present population with respect to airborne PAH concentrations or PAH-DNA adducts (see Table 2); however, they differed with respect to ethnic and residential distribution (see Table 1).

Exposure Assessment

Questionnaire. Questionnaires were administered by trained, bilingual personnel in the women’s homes during the third trimester in order to elicit information on demographics and history of active and passive smoking (14, 35).

Table 1. Demographic information for the CCCEH subset and total population

<table>
<thead>
<tr>
<th></th>
<th>Subset</th>
<th>Total population</th>
<th>P</th>
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<tbody>
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<td></td>
<td>n</td>
<td>Mean (range)</td>
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</tr>
<tr>
<td>Gender</td>
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</tr>
<tr>
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<td>32</td>
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<td></td>
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<tr>
<td>Male</td>
<td>28</td>
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<td>0.797</td>
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<tr>
<td>Maternal ethnicity</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>African American</td>
<td>30</td>
<td>388</td>
<td></td>
</tr>
<tr>
<td>Dominican</td>
<td>30</td>
<td>226</td>
<td>0.006</td>
</tr>
<tr>
<td>Maternal age (y)</td>
<td>60-28 (21-40)</td>
<td>685 28 (18-42)</td>
<td>0.186</td>
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<tr>
<td>Mother’s education1</td>
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<td>High school</td>
<td>43</td>
<td>463</td>
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</tr>
<tr>
<td>College</td>
<td>17</td>
<td>145</td>
<td>0.272</td>
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<tr>
<td>Neighborhood of residence</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Harlem</td>
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<td>248</td>
<td></td>
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<tr>
<td>Washington Heights</td>
<td>14</td>
<td>226</td>
<td></td>
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<tr>
<td>South Bronx</td>
<td>16</td>
<td>140</td>
<td>0.026</td>
</tr>
</tbody>
</table>

*Subset n = 60 mother-newborn pairs, Total population n = 686 mother-newborn pairs.

Air Monitoring. Personal air monitors were used to estimate individual exposures. The women were equipped with small personal air-monitoring devices for 48 hours during the third trimester of pregnancy. As previously described (14, 35), trained research personnel taught the women how to use the personal air-monitoring device. The women were asked to wear the backpack during the day for two consecutive days and to place the monitor near the bed at night. Motion sensors were placed in the backpacks of randomly selected women to assure compliance with the monitoring protocol. Vapors and particles of ≥2.5 m in diameter were collected, and extracts were frozen until analysis. Concentrations of eight carcinogenic PAHs [benz(a)anthracene, benzo(a)pyrene, benzo(b)fluoranthene, benzo(g,h,i)perylene, benzo(k)fluoranthene, chrysene, dibenz(a,h) anthracene, and indeno(1,2,3-cd)pyrene] were determined at the Southwest Research Institute using gas chromatography/mass spectrometry. Quantification of PAHs was done using calibration curves. Preestablished quality control measures were followed, and data determined to be questionable were not included in the statistical analysis. Briefly, flow rate, time, and completeness of documentation for each subject with respect to their personal air monitoring were evaluated for accuracy and given a numerical value of 0, 1, 2, or 3. Subjects’ air monitoring results rated as 2 or 3 were considered to be of intermediate or unacceptable quality and their data were excluded from further analysis. Air exposure monitoring for PAHs was completed for the 60 subjects in the subset population. However, in 3 cases the monitoring data were of inadequate quality due to analytic problems and were not included in the analysis.

Biomarkers. Blood was obtained from the umbilical cord (the portion attached to the placenta) immediately after the placenta was delivered. Approximately 30 mL of venous cord blood were drawn and transported immediately to the laboratory for processing and separation. One milliliter of whole cord blood was reserved for FISH (see below). The remainder of the cord blood was then separated for additional studies done as part of the CCCEH parent study. PAH-DNA adducts were measured using a high-performance liquid chromatography/fluorescence method that detects tetromers of benzo(a)pyrene (BaP), a representative PAH, in DNA extracted from WBCs in cord blood. This methodology is sensitive and specific for measurement of BaP-DNA adducts in WBC (36) with a COV% of 12% (14).

Cord Blood Culture. One milliliter of cord blood was placed in a heparinized Vacutainer and used for culture of phytohemagglutinin-stimulated lymphocytes, using standard techniques. Replicate cultures were done for each cord blood. Lymphocytes were cultured for 72 hours at 37°C, at which time the maximum number of cells reached metaphase. 0.1 mL colcemid was added to each culture 45 minutes before harvesting. After treatment of cells with hypotonic KCl and fixation in 3:1 methanol acetic acid, metaphase spreads were prepared by dropping on clean wet slides.

FISH Procedure. The whole chromosome probes used are available from Cytocell, Ltd. (Adderbury, Oxfordshire, United Kingdom) as a kit (Chromoprobe-M) containing coverslips coated with reversibly bound biotin and digoxigenin-labeled DNA probes for human chromosomes 1 to 6. Chromosomes 1 to 6 account for almost 40% of the DNA content in the entire genome; thus, theoretically, they are more likely to experience aberrant events than the other chromosomes, because the probability of a break(s) occurring in any particular chromosome is based on its DNA content. This has been seen in radiation research, which shows a linear relationship between DNA content and breakpoints, that is, larger chromosomes are subject to more breaks (37, 38).
FISH was carried out according to the manufacturer’s directions. Briefly, the prepared slides with well-spread metaphases were placed in a Coplin jar containing 2× SSC at room temperature for 2 minutes. The slides were then dehydrated for 2 minutes at room temperature in 70%, 85%, and 100% ethanol and rapidly dried. The Chromomend-M coverslips, the sample slides, and hybridization solution were prewarmed to 37°C; 10 µL of hybridization solution was added to each sample slide and the coverslip was immediately applied. The probes and target DNA were denatured on a hotplate at 75°C for 5 minutes and then incubated in a humid chamber overnight at 37°C. After removal of the coverslips, the slides were immersed in 0.4× SSC for 2 minutes at 72°C and then washed in 2× SSC with 0.5% NP40 for 30 seconds. Fifty microliters of detection reagent, mouse antidioginox green fluorophore conjugate mixed with streptavidin red fluorophore, were applied to each slide, glass coverslips were applied immediately, and the slides were incubated at 37°C in a humid chamber for 2 to 30 minutes. After washing, slides were immediately counterstained with 10 µL 4’,6-diamidino-2-phenylindole (DAPI)-Antifade solution and coverslipped (1, 2).

All metaphases were scored by one individual, who was blinded to all demographic and exposure information until aberration data collection was completed, using a 60× oil objective on a Nikon fluorescence microscope equipped with a filter wheel and a triple band-pass filter, which allows for concurrent visualization of chromosomes 1, 2, and 4 as red (Cy3), 3, 5, and 6 as green (FITC), and the remaining chromosomes as DAPI-counterstained (blue). Criteria for scoring of metaphases included unbroken cells with good spreading, complete visualization of all 2 painted chromosomes and their centromeres, and satisfactory intensity of probe signal. Ambiguities were resolved by image capture and analysis using an Applied Imaging Cytovision System, San Jose, CA. Coordinates were recorded for all cells with aberrations, as well as the type of aberration and chromosome involved. Chromosomes 1 to 6 were identified by their color (red for 1, 2, and 4; green for 3, 5, and 6; and blue for the remaining chromosomes), size, and relative arm length. For example, translocations were documented when two differently colored chromosome segments formed an aberrant chromosome, whereas deletions were recognized when one chromosome of the chromosome pair (for chromosomes 1-6 only) was markedly shorter in either arm compared with the other. Fragments were reported in chromosomes 1 to 6 when a small broken chromosome segment with no discernible centromere was visible.

To be consistent with prior research, 1,000 whole genome equivalents, or 1,800 metaphases, were scored per subject. “Whole genome equivalent” refers to the correction factor developed by Lucas et al. (38) that is applied to stable aberration frequencies detected by single-color FISH to adjust for those aberrations occurring in chromosomes that are not “painted” by the FISH probes and those aberrations involving chromosomes painted with the same color. Application of the correction factor is based on the assumption that the probability of a break(s) occurring in any particular chromosome is dependent on its DNA content; that is, larger chromosomes are subject to more breaks (37, 38). Whole genome equivalents for this study were determined by adapting the correction developed by Lucas et al. (38) to include the additional paint color used in this study rather than the single-color FISH used by Lucas et al.:
Statistical Analyses. The Wilcoxon rank sum test was used to analyze differences between groups defined by gender, ethnicity, smoking in the home by household members (yes/no) and passive smoking in the workplace (yes/no) with respect to continuous variables of exposure (PAHs in air and PAH-DNA adducts in cord blood), and outcomes (stable and unstable aberration frequencies). Spearman rank correlation was used to assess the relationship between the continuous exposure measures, as well as maternal age, and the continuous outcome variables. These initial statistical analyses were done using untransformed variables. Regression analyses were then done to evaluate the association between PAHs in air (log transformed to approximate the normal distribution) or PAH-DNA adducts (categorized as high/low using the median of detectable values as the cut point and nondetectables as a reference group) and aberration frequencies (stable aberrations square root transformed to approximate the normal distribution; unstable aberrations dichotomized). Unstable aberration frequency was dichotomized as absence versus presence of unstable aberrations, because >40% (26) of the subjects had no detectable level of unstable aberrations. Ethnicity (African American/Dominican) was related to stable aberration frequencies. However, stratified linear regression analyses of total PAHs in air and stable aberration frequencies by ethnic group showed similar \( \beta \) values for African Americans and Dominicans (0.12029 for African Americans, 0.14915 for Dominicans) although the association was only significant for Dominican newborns (\( P = 0.0228; P > 0.05 \) for African Americans). In addition, inclusion of ethnicity in the regression analysis of stable aberration frequencies and total PAHs in air did not significantly change the standard error or \( P \) value of the model. Therefore, ethnicity was not included in the final regression models. Maternal age was neither correlated with stable nor unstable aberration frequencies in cord blood, and was excluded from further analysis. Specifically, linear regression was applied to the continuous outcome variable (stable aberration frequency) and logistic regression was used for the dichotomous outcome variable (unstable aberration frequency).

Because of the high correlation between individual PAHs measured in air, a composite PAH variable was used, which was the sum of all eight carcinogenic PAHs measured in air listed in Table 2. Cronbach’s coefficient \( \alpha \) of 0.91, an average correlation of individual PAH measurements, indicated a high reliability of the composite variable.

Forty-eight subjects of the subset had an adequate amount of cord blood DNA for PAH-DNA adduct analysis. Of those, 26 newborns (54%) had nondetectable PAH-DNA adducts (<0.25 adducts per 10\(^8\) nucleotides). Among the subjects with detectable levels of PAH-DNA adducts (22 newborns), the distribution of the biomarker was skewed. Detectable adduct levels were categorized as high/low using the median of detectable adducts (0.4 adducts per 10\(^8\) nucleotides) as the cut point, with nondetectable subjects as the reference group. All tests were two tailed. All analyses were done using the SAS System, Version 9.0.

Results

As in the parent study (14, 35), there was variable prenatal exposure to PAHs in the subset as documented by personal air monitoring. Carcinogenic PAHs, including BaP, were detected in all of the air samples. Detectable levels of PAH-DNA adducts were found in 46% of cord blood samples (\( n = 22 \)). The air exposures and blood biomarkers ranged over several orders of magnitude. The mean and range of the exposure measures for total PAHs in air and PAH-DNA adducts in cord blood are shown in Table 2.

Bivariate correlation analysis revealed a positive and significant correlation between stable aberration frequencies, but not unstable aberrations, and total PAHs in air (Spearman correlation coefficient = 0.35, \( P < 0.01 \)). Detectable PAH-DNA adducts treated as a continuous variable were not significantly correlated with stable aberration frequencies (Spearman correlation coefficient = 0.03335, \( P = 0.8829 \)). The Wilcoxon rank sum test showed a small but nonsignificant increase in stable aberration frequencies in the “high” category compared with the “low” category for detectable PAH-DNA adducts (0.56 versus 0.45, respectively; \( P = 0.4810 \)).

ETS exposure at home was common. Almost half of the women (45%) in the subset reported a smoker in the home, whereas only 7% reported ETS exposure at work. Levels of stable and unstable aberration frequencies were not significantly different between those newborns whose mothers reported ETS exposure in the home or at the workplace and those who did not (Table 3).

Mean stable aberration frequencies for African American newborns were almost 50% greater than in Dominican newborns (\( P = 0.048 \); see Table 3). This increase was not seen in unstable aberration frequencies. Exposure levels of PAHs in air and PAH-DNA adducts did not differ significantly between African American and Dominicans (data not shown).

Regression analysis showed a positive association between PAH exposure in air and stable aberration frequencies in newborns, \( \beta = 0.1399, \text{SE} = 0.0491, P = 0.006 \) (see Fig. 1.). Also by linear regression, stable aberration frequencies and PAH-DNA adducts were not associated (data not shown), nor was there an association between unstable aberration frequency and either PAH exposure or PAH-DNA adducts (data not shown).

<table>
<thead>
<tr>
<th>Table 3. Results from Wilcoxon rank sum analyses of aberration frequencies and demographic and self-reported ETS exposure variables</th>
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<tbody>
<tr>
<td>Gender</td>
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<td>n</td>
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<tr>
<td>Female</td>
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<tr>
<td>Male</td>
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<tr>
<td>Ethnicity</td>
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<tr>
<td>African American</td>
</tr>
<tr>
<td>Smoker in the home</td>
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<tr>
<td>No</td>
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<tr>
<td>Smoker at the workplace</td>
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<tr>
<td>No</td>
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</table>

\* Wilcoxon scores (rank sums), \( t \) approximation two-sided.
portected chromosomal aberrations in cord blood and PAHs (log transformed) measured by 32P postlabeling, may not be adequately represented. We note that a prior study supporting BaP as a proxy, some PAH-related adducts may not be induced by the same ETS component(s), Finette Pluth et al. (0.11%; ref. 2) and Ramsey et al. (0.2%; ref. 2), and six times that reported by Pluth et al. (0.11%; ref. 1) in 14 and 40 newborns, respectively. Although there have been differences in exposures and/or ethnic compositions between the study populations, Pluth et al. (1) and Ramsey et al. (2) provide exposure data only on smoking status and no information on the racial/ethnic background of their study populations. The most likely explanation for the higher level of chromosomal aberration frequencies in the present study is that Ramsey et al. (2) and Pluth et al. (1) included only translocations and insertions in their scoring criteria, whereas the present study included translocations, insertions, and deletions. Moreover, those investigators used FISH whole chromosome probes, which painted only chromosomes 1, 2, and 4, whereas chromosomes 1 to 6 were painted in the CCCEH population. Despite these differences in absolute values, all three studies show a significant increase in chromosomal aberrations after prenatal exposure to environmental mutagens/carcinogens.

Finally, no significant associations were found with any of the exposure measures and unstable aberration frequencies. Unstable aberrations are considered less relevant to future cancer risk than stable aberrations. Unstable aberrations are essentially a measure of chromosome fragments that are indicative of past chromosome breaks but are transient markers of cytogenetic damage, which are not perpetuated in further cell divisions. In contrast, stable aberrations such as translocations and deletions are persistent, reflect past exposures, and can lead to cancer (2, 45-47).

In conclusion, this study has showed a significant association between prenatal environmental exposure to airborne carcinogenic PAHs and stable aberrations in cord blood at the relatively low environmental concentrations found in New York City. Because similar air concentrations are found in other urban areas in the United States and Europe (48), the results have relevance to other populations.

Acknowledgments

We thank Antonio Sobrino, Taknida Tubo, and the Cytogenetics Laboratory staff of New York Presbyterian Medical Center (Columbia University); Jing Lai, Lirong Qu, and Xinhe Jin from the laboratory of Dr. Deliang Tang; and Dr. Robin Garfinkel and Lori Hoepner from the Data Management, Statistics & Community Impact Modeling Core.

References


