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Risk of Cancer as a Result of Community Exposure to Gasoline Vapors

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ABSTRACT. The Tranguch Gasoline Spill leaked 50,000–900,000 gallons of gasoline from underground storage tanks, potentially exposing an area of Hazle Township and Hazleton, Pennsylvania, to chronic low levels of benzene since at least 1990. A retrospective cohort study of 663 individuals representing 275 households assessed whether affected residents were at increased risk for cancer from 1990–2000 compared with the Pennsylvania populace. Age-adjusted standard incidence ratios (SIRs) were calculated using Pennsylvania rates to determine expected numbers. The age-adjusted SIR for the gasoline-affected area was 4.40 (95% confidence interval: 1.09–10.24) for leukemia. These results suggest an association between living within the area affected by the Tranguch Gasoline Spill and increased risk for leukemia.
<Key words: benzene, cancer, community, gasoline, leukemia>

LEAKING underground petroleum storage tanks are a frequent and serious problem. Petroleum leaking from these tanks contaminates surrounding soil and groundwater causing both environmental and health risks. In an effort to address the growing problem of leaking underground tanks, Congress created the Leaking Underground Storage Tank Trust Fund to assist with cleanup efforts. Between the inception of this program in 1986 and September 30, 2004, the United States Environmental Protection Agency (EPA) identified 447,233 such releases, and estimated cleanup had been completed for only 71% of these releases.[1]

Given the prevalence of such releases, and the fact that nearly half of the U.S. population depends on groundwater as a primary drinking water source, it is highly probable that many communities continue to face potential health effects as a result of volatile organic compounds from these leaking petroleum sources.[2] The public health effects of such leakages, however, have not been well documented or studied. This article reports on the health effects of one community's exposure to gasoline leaked from underground storage tanks.

In response to several odor complaints by residents of Hazle Township and the city of Hazleton, both situated in northeastern Pennsylvania, in 1991, the Pennsylvania Department of Environmental Protection (PADEP) began a series of investigations into what would become known as the Tranguch Gasoline Spill or the Tranguch Spill, which affected residents in two municipalities, Hazleton and Hazle Township. The spill was characterized as a leakage of 50,000 to 900,000 gallons of gasoline from underground storage tanks. A plume of groundwater contamination was detected, and consequent filtration into the sanitary sewer system was identified. It is believed that between 1990 and 2000 residents within the Tranguch Spill area were chronically exposed to low levels of benzene, a known carcinogen, and other organic solvents as a result of the leaking

gasoline. The spill was characterized by the Pennsylvania Department of Environmental Protection. The period of exposure is in doubt since the gasoline had already leaked when it was identified. There is a lack of environmental exposure data to confirm these years and modeling predictions.

Within the United States it has been estimated that the benzene content in gasoline is approximately 1–2% by volume.[3] Global average benzene estimates range from 5 $\mu g/m^3$ for outdoor levels to 15 $\mu g/m^3$ for personal levels.[4-6] Workplace exposures may be of higher concentration and shorter duration than those experienced by the general population.

Epidemiological studies have found elevated standardized incidence ratios (SIR) for leukemia among large occupational cohorts exposed to benzene concentrations greater than 200 ppm-yr.[7-9] equivalent to a crude average of 10 ppm benzene exposure over 20-yr working at one job. Hayes et al. also found an increased risk of all hematologic cancers in a cohort of workers exposed to benzene at average levels below 10 ppm.[10]

Several occupational studies have also documented hematotoxic effects at levels of benzene under 1 ppm.[11-14] Glass et al. found evidence for an increased risk of leukemia among Australian petroleum workers whose highest intensity job exposure to benzene was 0.8 ppm.[14] Unlike previous occupational cohorts, this cohort provided evidence for risk of leukemia associated with cumulative exposure to benzene at any level, with no obvious threshold. Moreover, Lan et al. demonstrated a significant depression (~15%) in white cell counts among Chinese shoe factory workers with less than 1 ppm benzene job exposure,[11] further corroborating the plausibility of adverse hematopoietic effects as a result of low-level exposure to benzene.

Ecological studies have found increased risk for leukemia in areas with elevated concentrations of benzene in the air or high traffic density and subsequent gasoline exposure. Such studies typically suffer from ecological fallacy, deficiencies in case ascertainment, and crude exposure estimates.[15-21] However, they aid in the identification of high-risk areas, which can then be studied in more detail.

The literature is limited with respect to community exposures such as that experienced by Tranguch Gasoline Spill area residents. This exposure was low level (in the range of parts per billion) and long term. The Tranguch Gasoline Spill exposure was also unique in that the geology of the area, consisting of underground coal mining and shallow bedrock, may have facilitated pooling of gasoline below the surface of the affected area, thus increasing subsequent migration into groundwater and sewer systems and the probability of exposure. In a similar situation Lindstrom et al. found benzene concentrations of 0.8–1.7 ppm (758–1,670 $\mu g/m^3$) within the shower stall of a household using gasoline-contaminated groundwater.[22] No link, however, was made between exposure and health outcomes in that report. The focus of the current research was to determine whether residents of the Tranguch Spill-affected area were at increased risk for cancer compared with standard reference populations and to assess the prevalence of additional adverse health outcomes among the residents.

Method

Benzene exposure estimates. Prior to EPA remediation efforts, PADEP tested the indoor air of a subset of 43 homes for the concentration of volatile organic compounds (VOCs) over the course of 72 d (49 sampling d) in 1993. The sampling device used was an Hnu photo ionization detector (PID), which does not measure individual species of VOCs such as benzene, although these measurements can be extrapolated. Concentrations of total VOCs ranged from 0 to 202 ppm and estimated benzene concentrations ranged from 0 to 42 ppm (0–136 mg/m^3).[23]

Benzene levels in the groundwater of the Tranguch Spill area were estimated by EPA and The U.S. Army Corps of Engineers through exposure-modeling conducted between 1994 and 1996. Groundwater estimates of benzene ranged from 200 to 2,500 $\mu g/m^3$.[23] Using this information and taking into consideration possible vapor migration through the sanitary sewer system, EPA defined a remediation or "affected" area of 366 households within the Hazle Township and Hazleton municipalities potentially exposed to gasoline fumes as a result of the Tranguch Spill.

In late 2000 and January 2001 EPA sampled indoor air in these homes, using Summa canisters, to assess concentrations of benzene. Reports on these samples were provided to investigators by approximately 20% of homeowners. Benzene levels ranged from undetectable (<8.3 $\mu g/m^3$) to 140 $\mu g/m^3$ in the sample of homes for which owners released their results. However, cumulative benzene exposure among residents cannot be adequately estimated because there are no comprehensive historical data on air and groundwater concentrations of benzene and duration of exposure. Therefore, exposure to benzene from the leaking tanks was defined by residence within the EPA-defined remediation area.

Study design, area, and target population. A retrospective cohort study design was employed because the exposure took place years before study commencement; the adverse health endpoints being considered are rare and have long latencies (e.g., cancer), and the method optimizes the small sample size. The cohort was constructed from tax records, municipal lists, and residential histories of persons living for at least 6 mo within the EPA remediation or affected area from January 1, 1990, through December 31, 2000. A total of 366 properties were within the boundaries of the affected area.

After validation of properties eligible for study inclusion, 17 were identified as nonresidential and their owners were thus excluded from the target population. The overall current property owner response rate was 80%. Of the 72 households that did not participate, 42 owners refused to participate and 30 could not be contacted after multiple attempts.

In addition, 72 properties had changed ownership within the study period. Several attempts were made to contact the 62 past owners of these 72 properties; 3 agreed to participate in the study.

Data collection. Because of the funding mechanisms of local municipalities, data collection and analysis were conducted independently using the same methodology. A study-specific questionnaire was developed to assess demographics and primary and secondary health outcomes. Questions dealt with residential, employment, medical, reproductive, and smoking history; education level; and symptom experiences. Participants also were asked to complete a medical record release form to allow the researchers to obtain confirmation of self-reported cancers through participants' physicians. The study and data collection materials were reviewed and approved by the University of Pittsburgh Biomedical Institutional Review Board.

Data was collected in the summer of 2001 for Hazle Township properties and the summer of 2002 for Hazleton properties. Within each household all individuals aged 18 yr and older were asked to read and sign the consent form, sign the medical release form, complete the questionnaire, and return the forms to the University of Pittsburgh in a preaddressed stamped envelope. Parents or guardians were asked to complete the questionnaire for children under the age of 18. Proxy interviews from next of kin were conducted for persons unavailable or unable to complete the forms. A death certificate was requested for all deceased individuals. For individuals who did not respond to the initial mailing of study materials, researchers made follow-up telephone calls and sent reminder postcards. To accommodate participants with little time for completion of a full study-questionnaire, an abbreviated questionnaire addressed gender; race; marital status; date of birth; occupation; vital status; smoking and residential history; and history of cancer, diabetes, and other chronic diseases for all household members on a single form.

Incident cancer, the primary outcome, was identified via the questionnaires. For all self-reported cancers researchers contacted the participant's attending physician for verification of the cancer diagnosis and to request the release of participant's medical records. In addition, a request was made to the Pennsylvania Department of Health for the confirmation of all self-reported cancers using data from the Pennsylvania Cancer Registry. Cancers were classified in a manner similar to that of the Pennsylvania Cancer Registry employing International Classification of Diseases for Oncology (ICD-O) codes.

Information was also obtained on those persons who died during the 11-yr period for whom we could obtain next-of-kin interviews and a death certificate. A death certificate for all deceased individuals was obtained from the Pennsylvania Department of Vital Statistics.

Statistical analyses. Descriptive population statistics such as frequencies, means, and medians were generated using SPSS version 12.0 for Windows® (SPSS, Inc., Chicago, IL). The unit of analysis for the cancer incidence measures was the person-year. SAS version 8.0 (SAS Institute, Inc., Cary, NC) was used to determine the number of person-years contributed by each individual. Individuals residing within the study area from January 1, 1990, to December 31, 2000, contributed 11 person-years. Other individuals who moved into or out of the area within this period contributed varying person-years on the basis of their residential history. Individuals no longer accumulated person-years after they had been diagnosed with cancer or identified as deceased.

To characterize the cancer experience of residents, standard incidence ratios (SIRs) were calculated. These were based on self-reported, physician- and Pennsylvania Cancer Registry-verified cancer diagnoses from 1990–2000 and the expected number of cancers derived from indirect age-adjustment using Pennsylvania average annual cancer incidence rates. Confidence intervals (CI) were determined using Poisson tables in the Documenta Geigy.[24] Statistical significance was defined as $p < .05$.

Results

A total of 663 persons from 275 households participated in the study. More than 63% of participants completed the full questionnaire with the remainder completing the abbreviated version. The population was 99% Caucasian, and comprised of 343 (51.7%) women and 320 (48.3%) men. The mean age of the population alive at time of interview ($N = 625$) was 49.2 yr ($SD \pm 22.1$ yr), and the period of residence within was (mean $\pm$ SD) 36.7 $\pm$ 21.9 yr (Table 1). The distribution of residents by years of residence within the affected area is presented in Table 2. The majority of residents were married with at least a high school education. More than 36% of men and 27% of women reported a history of smoking. Fifty-four percent of participants were employed with the remainder comprised of retirees, students, and unemployed persons. Twelve residents reported prior employment at a gasoline station.

Causes of death for 38 individuals who had lived in the study area between 1990 and 2000, for whom proxy interviews were obtained were cardiovascular disease ($N = 14$), cerebrovascular disease ($N = 2$), chronic obstructive pulmonary disease ($N = 2$), pneumonia ($N = 2$), cancer ($N = 13$), and other diseases ($N = 5$).

Table 1.—Age Distribution of Population Alive at Time of Data Collection with Mean Age and Mean Years of Residence within Affected Area by Age Group

Age Group	*N*	Mean Age	*SD*	Mean Years of Residence	*SD*
			Men		
<18	40	11.0	4.7	10.1	4.9
18–34	63	26.3	5.1	22.3	7.3
35–44	37	40.7	2.9	33.9	12.6
45–54	38	49.8	2.7	32.9	17.2
55–64	37	59.5	3.1	40.4	17.5
65–74	49	69.9	3.2	50.9	17.8
75+	30	79.6	3.4	56.4	25.6
Total	294	46.0	22.4	34.3	21.0
			Women		
<18	30	11.5	4.0	10.0	4.3
18–34	47	27.3	4.8	23.9	6.8
35–44	42	40.5	2.6	30.8	13.6
45–54	47	50.5	3.3	33.3	16.3
55–64	54	60.3	3.0	43.6	16.5
65–74	57	70.1	3.1	50.0	20.4
75+	54	79.4	3.3	61.8	23.6
Total	331	52.1	21.3	38.8	22.5
			Total		
<18	70	11.3	4.4	10.0	4.6
18–34	110	26.7	5.0	23.0	7.1
35–44	79	40.6	2.8	32.2	13.1
45–54	85	50.2	3.0	33.1	16.6
55–64	91	60.0	3.1	42.3	16.9
65–74	106	70.0	3.1	50.4	19.2
75+	84	79.4	3.3	59.9	24.3
Total	625	49.2	22.1	36.8	21.9

Table 2.—Distribution of Residents by Years of Residence within Affected Area

Years of Residence	Men	Women	Total
<5	14	12	26
5–9	14	19	33
10–19	53	41	94
20+	200	254	454
Total	281	326	607

Forty-three incident primary cancers were reported within the cohort and verified by the Pennsylvania Cancer Registry for the period of January 1, 1990, through December 31, 2000. The participants with cancer included two with acute myeloid leukemia (66 and 67 yr at diagnosis), one with chronic myeloid leukemia (64 yr at diagnosis) and one with chronic lymphocytic leukemia (75 yr at diagnosis). The residences of the two participants with acute myeloid leukemia bordered the projected gasoline plume, which was within the affected area. None of the four participants with leukemia had a history of working in a benzene-exposed occupation and no parental history of cancer was reported. Two of the participants with leukemia had a history of smoking.

The SIRs for all cancers are presented in Table 3. The SIR for all cancer sites was 0.88 [95% confidence interval: 0.64–1.18], indicating no statistically significant difference in all-site cancer incidence in the Tranguch Spill area and the State of Pennsylvania. The SIR for leukemia was 4.40 (95% confidence interval: 1.09–10.24) a difference from the incidence in the affected area, which is statistically significant. Differences between cancer incidence in the affected area and the state of Pennsylvania for all other cancer sites were not statistically significant, although the SIRs for all observed cancers except those of the respiratory tract and colon were greater than 1.

We also assessed the prevalence of health effects other than cancer. With the exception of diabetes, disease/disorder information was only available for 69% of the study population, those who completed the full questionnaire. Among the 456 individuals who were asked about disease/disorders other than cancer, 135 (20.4%) reported having diagnosed hypertension, 68 (10.3%) reported a diagnosis of cardiovascular disease other than stroke, and 16 (2.4%) reported a history of stroke. Additionally, 44 (6.6%) reported a doctor-diagnosed thyroid problem, and 44 (6.6%) reported diagnosed anemia. Diabetes information was available for 659 participants of whom 46 (6.9%) reported having the disease.

Discussion

The age-adjusted all-cause cancer incidence within the Tranguch Spill-affected area was not significantly different from that for the state of Pennsylvania but that for leukemia was significantly higher than state incidence. Our findings are consistent with those in the literature that suggest long-term exposure to low levels of benzene, a constituent of gasoline, may be associated with increased risk of hematopoietic malignancies, particularly acute myeloid leukemia.[14,20,27]

These results are also consistent with a similar report by the Pennsylvania Department of Health (PADOH) that considered cancer incidence within the Tranguch Spill area from 1985 to 2002.[28] A total of 134 cancer cases were identified in the PADOH study. The SIR for all causes of cancer was 1.31 and was statistically significant. Additionally, seven incident cases of leukemia were observed, resulting in an SIR of 3.63, also statistically significant. Of these seven cases, three were acute-myeloid in cell type and two were chronic myelocytic. PADOH did not, however, ascertain complete residential histories for the population as we did and thus, may have overestimated the number of person-years, by making the assumption that people had resided in the area for all 11 years or that those under 11 yr had person-years equivalent to their ages.

Despite different methods of ascertaining person-year, our analysis and the PADOH study suggest an association between low-level chronic benzene exposure and

Table 3.—Standard Incidence Ratios for Population of the Area Affected by Tranguch Spill Compared with the State of Pennsylvania

Cancer	Observed Cases	Expected Cases*	Standard Incidence Ratio	95% Confidence Interval
Leukemia	4	0.91	4.40	1.09–10.24
Non-Hodgkin's lymphoma	2	1.62	1.23	0.15–4.46
Trachea, bronchus, lung, & pleura	5	7.47	0.67	0.22–1.56
Colon	3	4.60	0.65	0.13–1.91
Urinary bladder	3	2.35	1.28	0.26–3.73
Brain	2	0.55	3.64	0.44–13.13
Stomach	2	1.12	1.79	0.21–6.45
Female breast	12	7.89	1.52	0.79–2.66
Cervix	1	0.38	2.63	0.08–14.66
Prostate	9	7.12	1.26	0.58–2.40
All cancer sites	43	49.1	0.88	0.64–1.18

*Expected cases for the state of Pennsylvania.

leukemia risk within the Tranguch Spill-affected area based primarily on existing literature on the subject and the lack of any other common source explanation. However, these findings should be interpreted in the context of study limitations. The exposure that occurred as a result of the Tranguch Gasoline Spill is not well characterized. After identification of the spill, attempts were made by PADEP and EPA to assess the VOC and benzene exposure. However, the exact commencement date of the spill, as well as the concentration and extent of benzene exposure remains unknown.

Although PADEP assessed VOCs in indoor air within 43 homes in the affected area during 1993–1994, the frequency and duration of each exposure within a home were not well documented and benzene was not differentiated. The Agency for Toxic Substances and Disease Registry (ATSDR) of the U.S. Department of Health and Human Services used benzene concentrations extrapolated from PADEP VOC measurements to estimate maximum benzene exposure at 42 ppm with an average level of 0.16 ppm.[23] For a 3-yr period, this translates to 2 ppm-yr for a maximum exposure and 0.03 ppm-yr for an average exposure. The agency concluded that prior to remediation, these benzene exposures might have been high enough to produce adverse health effects.[23]

EPA conducted additional sampling within all households in the remediation area in 2000–2001 using more sophisticated sampling techniques such as Summa canisters. However, these samples were taken at one time and only in one or two locations within the home and potentially years after peak exposure. Thus, they may not reflect the actual exposure concentration over time, nor do they adequately reflect historical levels of benzene prior to remediation efforts.

The remediation area was defined on the basis of a combination of groundwater sampling and exposure estimation models. These groundwater samples were taken at least 5 yr after the suspected commencement of the spill, and therefore may underestimate the original extent and concentration of benzene exposure. Given the lack of historical benzene exposure data and the necessity to identify an objective exposure area for a health effects study, we used the EPA-defined remediation area as our "affected area." Because of the limitations of the exposure assessment, this area may over- or underestimate the population exposed to gasoline.

Limitations of our study were the lack of an appropriate control population to adjust for confounders and to compare the frequency of health issues other than cancer such as anemia and hypertension.

This research provides potential evidence of an increase in hematopoietic cancer risk as a result of longer-term exposure to low concentrations of benzene. Although the benzene exposure was not well-characterized at an individual level, this research did not suffer from the ecological fallacy observed in other community studies investigating gasoline/benzene exposure and leukemia.[15–21] This is in agreement with occupational studies that have documented hematopoetic risk at similar levels.[11–13]

Within a population of 250 Chinese workers exposed to benzene—even as low as <1 ppm in the air—white blood cell, granulocyte, lymphocyte, B cell, and platelet counts were depressed compared with unexposed controls. Such effects may lead to more serious hematopoietic consequences such as leukemia. Although an increase in the risk of leukemia as a result of exposure to low-level benzene remains equivocal,[7,29–32] our study provides support for the growing body of evidence suggesting a causal link.[14,17,21]

To address the health concerns of residents affected by the Tranguch Spill we recommend continued surveillance of cancer, particularly leukemia and its precursors, within the affected population until 2010 to capture any

latent cancers, confirm incidence rates, and narrow the confidence interval for SIR calculations. Data from the Pennsylvania Cancer Registry alone will not capture non-cancer health effects caused by benzene, such as aplastic anemia and myelodysplastic syndrome.

As part of this surveillance effort a combination of active and passive reporting of specific medical conditions including leukemia, anemia, and myelodysplastic syndrome would be instituted. Complete blood counts and other medical testing determined to be appropriate also would be conducted every 6 mo or annually. Surveillance might also include screening for biomarkers of hematologic disease susceptibility (xenobiotic enzyme polymorphisms), biomarkers of early hematological effects of benzene exposure (chromosomal aberrations), and evidence of environmental benzene exposure (glycophorin A, benzene-related DNA adducts, and urinary excretion products).[33–36] A further recommendation is to continue systematic surveillance over a longer follow-up period for individuals potentially at the greatest risk for leukemia such as children, the elderly, individuals with comorbidities, and residents living over or adjacent to the projected gasoline plume boundary. ATSDR also supported systematic surveillance for cancer in the affected area.[23]

This research is one of very few studies to extensively investigate exposures to gasoline/benzene in a community setting. Given the high prevalence of leaking underground gasoline tanks in the United States, this exposure is far from unique. Therefore, it is important for communities and public health agencies to cooperate to assess and address health effects potentially resulting from such leaks.

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References

1. Rothenstein C [2004]. Memorandum of November 24, 2004, from Cliff Rothenstein, Director Office of Underground Storage Tanks, to UST/LUST Regional Division Directors, Regions 1–10. Subject: FY 2004 Semi-Annual End-of-Year Activity Report for the Underground Storage Tanks Program. Washington, DC: U.S. Environmental Protection Agency.
2. U.S. Environmental Protection Agency (EPA). The Occurrence of Volatile Synthetic Organic Chemicals in Drinking Water. Washington, DC: EPA, 1981.
3. Krewski D, Snyder R, Beatty P, et al. Assessing the health risks of benzene: a report on the benzene state-of-the-science Workshop. J Toxicol Environ Health Part A 2000; 61:307–38.
4. U.S. Environmental Protection Agency (EPA). National Ambient Volatile Organic Compounds Data Base Update (Report No.: 600/3-88/010a). Washington, DC: EPA, 1988.
5. Wallace LA. The TEAM Study: Summary and Analysis: Vol. 1 (EPA 600/6-87/002a). 1987. Washington, DC: U.S. Environmental Protection Agency, 1987.
6. Wallace L. Environmental Exposure to Benzene: An Update. Environ Health Perspect 1996; 104(suppl. 6):1129–36.
7. Wong O. Risk of acute myeloid leukemia and multiple myeloma in workers exposed to benzene. Occup Environ Med 1995; 52(6):380–4.
8. Rinsky RA, Smith AB, Hornung R, et al. Benzene and leukemia: an epidemiologic risk assessment. New Engl J Med 1987; 316:1044–50.
9. Yin S, Hayes R, Linet M, et al. A cohort study of cancer among benzene-exposed workers in China: overall results. Am J Ind Med 1996; 29:227–35.
10. Hayes RB, Yin S-N, Dosemeci M, et al. Benzene and the dose-related incidence of hematologic neoplasms in China. J the Nat Cancer Inst 1997; 89(14):1065–71.
11. Lan Q, Zhang L, Li G, et al. Hematotoxicity in workers exposed to low levels of benzene. Science 2004; 306:1774–6.
12. Ward E, Hornung R, Morris J, et al. Risk of low red or white blood cell count related to estimated benzene exposure in a rubberworker cohort (1940–1975). Am J Ind Med 1995; 29(3):247–51.
13. Qu Q, Shore R, Li G, et al. Hematological changes among Chinese workers with a broad range of benzene exposures. Am J Ind Med 2002; 42:275–85.
14. Glass DC, Gray CN, Jolley DJ, et al. Leukemia risk associated with low-level benzene exposure. Epidemiology 2003; 14(5):569–77.
15. Swaen G, Slangen J. Gasoline consumption and leukemia mortality and morbidity in 19 European countries: an ecological study. Int Arch Occup Environ Health 1995; 67:85–93.
16. Nordlinder R, Jarvholm B. Environmental exposure to gasoline and leukemia in children and young adults: an ecology study. Int Arch Occup Environ Health 1997; 70:57–60.
17. Westley-Wise V, Stewart B, et al. Investigation of a cluster of leukemia in the Illawarra region of New South Wales, 1989–1996. Med J Aust 1999; 171(4):178–83.
18. Pearson R, Wachtel H, et al. Distance-weighted traffic density in proximity to a home is a risk factor for leukemia and other childhood cancers. J Air Waste Manag Assoc 2000; 50(2):175–80.
19. Harrison R, Leung P, et al. Analysis of incidence of childhood cancer in the West Midlands of the United Kingdom in relation to proximity to main roads and petrol stations. Occup Environ Med 1999; 56(11):774–80.
20. Crosignani P, Tittarelli A, Borgini A, et al. Childhood leukemia and road traffic: a population-based case-control study. Int J Cancer 2004; 108:596–9.
21. Parodi S, Vercelli M, Stella A, et al. Lymphohaematopoietic system cancer incidence in an urban area near a coke oven plant: an ecological investigation. Occup Environ Med 2003; 60:187–93.
22. Lindstrom A, Highsmith V, Buckley T, et al. Gasoline-contaminated groundwater as a source of residential benzene exposure: a case study. J Expos Anal Environ Epidemiol 1994; 4(2):183–95.
23. Agency for Toxic Substances and Disease Registry (ATSDR). ATSDR Tranguch Workgroup Report: Review of the University of Pittsburgh Recommendations Regarding

Leukemia in the Community Affected by the Tranguch Gasoline Spill. Atlanta, GA: ATSDR, 2004.
24. Diem K, Lentner C (editors), Documenta Geigy: Scientific Tables, 7th ed. Basle, Switzerland: Ciba-Geigy Limited, 1972.
25. Savitz DA, Andrews KW. Review of epidemiologic evidence on benzene and lymphatic and hematopoietic cancers. Am J Ind Medi 1997; 31(3):287–95.
26. Lamm S, Walters A, Wilson R, et al. Consistencies and inconsistencies underlying the quantitative assessment of leukemia risk from benzene exposure. Environ Health Perspect 1989; 82:289–97.
27. Mehlman MA. Benzene: a haeomatopietic and multi-organ carcinogen at any level above zero. Eur J Oncol 2004; 9(1):15–36.
28. Pennsylvania Department of Health. Tranguch Cancer Incidence Study: Updated through 2002. Harrisburg, PA: Pennsylvania Department of Health, 2003.
29. Collins JJ, Ireland B, Buckley CF, et al. Lymphohaematopoeitic cancer mortality among workers with benzene exposure. Occup Environ Med 2003; 60:676–9.
30. Schnatter AR, Armstrong TW, Thompson LS, et al. The relationship between low-level benzene exposure and leukemia in Canadian petroleum distribution workers. Environ Health Perspect 1996; 104(suppl 6): 1375–9.
31. Raabe GK, Wong O. Leukemia mortality by cell type in petroleum workers with potential exposure to benzene. Environ Health Perspect 1996; 104(suppl 6): 1381–92.
32. Lynge E, Andersen A, Nilsson R, et al. Risk of cancer and exposure to gasoline vapors. Am J Epidemiol 1997; 145(5):449–58.
33. Zhang L, Eastmond DA, Smith MT. The nature of chromosomal aberrations detected in humans exposed to benzene. Crit Rev Toxicol 2002; 32(1):1–42.
34. Qu Q, Melikian AA, Li G-L, et al. Validation of biomarkers in humans exposed to benzene. Am J Ind Med 2000; 37:522–31.
35. Pezzagno G, Maestri L, Fiorentino ML. Trans, trans-muconic acid, a biological indicator to low levels of environmental benzene: some aspect of its specificity. Am J Ind Med 1999; 35:511–18.
36. Smith M, Zhang L. Biomarkers of leukemia risk: benzene as a model. Environ Health Perspect 1998; 106(suppl 4): 937–46.