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Potential Exposure to Environmental Toxic Emissions and Increased Cancer Risk in Puerto Rico

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Abstract

Background: Toxic environmental pollutants are a risk factor for some cancers. We conducted an ecological study to assess the cancer risk in Puerto Rico after 15 years of exposure.

Methods: Cancer incidence data (2018–2022) were obtained from the Puerto Rico Central Cancer Registry. Contaminated areas were defined as municipalities with industrial facilities reporting on-site toxic chemical emissions to the Environmental Protection Agency's Toxic Release Inventory (TRI) from 2006 to 2020. We estimated cancer risk using the age-standardized incidence relative risk (RR) with 95% confidence intervals (95%CI) by cancer type and sex. This was repeated for the frequency of onsite TRI emissions (none, intermittent, and continuous). All were performed using SEER*Stat v8.4.4.

Results: Between 2018 and 2022, 80,179 invasive cancer cases were diagnosed in Puerto Rico. Residents of contaminated municipalities had a 7% higher risk of all cancer types (RR: 1.07, 95%CI: 1.05–1.09) than those in non-contaminated municipalities, similar to females (RR: 1.05, 95%CI: 1.02–1.07) and males (RR: 1.10, 95%CI: 1.07–1.12). Risk was higher in highly contaminated municipalities, with a 5% increase in females (RR=1.05, 95%CI: 1.03–1.08) and 12% in males (RR=1.12, 95%CI: 1.09–1.15).

Conclusions: The data suggest higher cancer rates in municipalities with TRI facilities, emphasizing the need for research, environmental interventions, and public health actions to mitigate toxic chemical exposure in Puerto Rico.

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Impact: This study contributes additional knowledge of Puerto Rico's cancer burden by identifying the relationship that may exist between living in municipalities with industries reporting the emission of toxic chemicals and cancer risk.

Keywords

Cancer risk; Environmental pollution; Industrial emissions; Toxic Release Inventory (TRI); Puerto Rico

INTRODUCTION

In the Caribbean, cancer accounts for a fifth of all deaths, and its incidence is increasing [1]. People diagnosed with cancer in this region face unique challenges in their prevention and control efforts [2]. Puerto Rico, a United States (US) territory in the Caribbean Sea, has a history of environmental and societal neglect and a disproportionate impact from climate-driven extreme weather events [3]. It is home to almost 3.2 million Hispanics/Latinos [4]. From 2000 to 2022, 320,076 cancer cases were diagnosed: for men the age adjusted incidence rate increased from 348.3 to 377.6 per 100,000; for women from 252.9 to 314.5 per 100,000 [5]. Although the overall cancer mortality in Puerto Rico decreased from 2016 to 2020, its incidence has increased annually [6]. Among females, significant increases in cancer incidence include breast (Annual Percentage Change [APC]=1.7%), corpus and uterus (APC=4.6%), thyroid (APC=9.0%), non-Hodgkin lymphoma (APC=2.1%), pancreas (APC=3.1%), leukemia (APC=2.7%), and ovary (APC=0.8%). Among men, significant increases were observed in the prostate (APC=1.7%), non-Hodgkin lymphoma (APC=1.8%), liver and bile duct (APC=1.9%), kidney and renal pelvis (APC=4.3%), leukemia (APC=2.2%), and pancreas (APC=2.2%). Municipalities in the southern, northern, and central regions of Puerto Rico have the highest cancer incidence rates [6]. Although cancer risk is influenced by multiple factors, including genetics, environment, medical history, and lifestyle [7], previous studies have highlighted a disproportionate environmental pollution burden on Black and Hispanic/Latino populations [8–12]. Therefore, identifying environmental risk factors in Puerto Rico is a public health priority, as they have been associated with genitourinary, digestive, gastrointestinal, gynecological, hematologic/blood, and breast cancers (Table S1) [13–18].

The presence of chemicals in the air, water, or soil occurs naturally. However, most carcinogen-related substances originate from anthropogenic activities, such as manufacturing and other industrial processes. Historical data (1987–2023) reported to the US Environmental Protection Agency's (EPA) Toxic Release Inventory (TRI) program include emissions from 27 industry sectors, with electric utilities, chemical and petroleum industries, hazardous waste facilities, and manufacturing as the top pollutant sources in Puerto Rico. However, exposure to pollution or healthier environments is not equally spread across space [19–21]. Exposure to carcinogens is uneven and often affects socially and economically disadvantaged populations [22–23, 10]. This unequal exposure highlights that communities and populations are vulnerable to systemic factors beyond their control, leading to differential and preventable health disparities [24]. While global studies have

linked proximity to industrial pollution with increased cancer risk, this association has not been fully studied in Puerto Rico.

Environmental pollution, including the presence of carcinogens and their mixtures, has been documented across the archipelago of Puerto Rico [25–26] with varying exposure by municipality [27]. For example, a 2009 ecological study found that residents of Vieques, an island municipality located 11 km off the east coast of Puerto Rico's main island, had a 26% higher risk of cancer than those on the main island [28]. Despite the differences found in the study between the municipality of Vieques and Puerto Rico, which may be attributed to higher concentrations of toxic metals in the soil and exposure to munition-specific carcinogens following US military exercises [29–30], no other epidemiological studies have been conducted to estimate cancer incidence in Puerto Rico. Meanwhile, communities in industrial zones across Puerto Rico's main island are exposed to a complex mixture of toxic emissions that pollute the environment and pose health risks, including an increased risk of cancer [31–33].

The TRI program regulates and monitors toxic emissions in the US and its territories for 799 individual chemicals and 33 chemical categories [34]. According to the TRI [35], 199 facilities in Puerto Rico with unique identification numbers (TRIFID) submitted report forms to the TRI between 2006 and 2020. Of these, 160 reported on-site emissions. During this period, approximately 75.8 million pounds of emissions from 122 chemical substances were released across the archipelago. Of these, 60.6 million pounds of emissions from 114 chemical substances were reported to have been released on-site in 48 of the 78 municipalities of Puerto Rico. The Occupational Safety and Health Administration (OSHA) classifies 33 of the 114 chemicals emitted as carcinogens [36], representing 26% of the total releases in Puerto Rico for the historical data (1987–2023) reported. These chemicals enter environmental compartments (soil, water, and air), affecting human health, especially as climate change is likely to increase human exposure to carcinogenic substances, posing risks to Caribbean populations [37, 2]. Although environmental health assessments suggest that prolonged exposure to chemical substances can lead to worse health outcomes, epidemiological studies have demonstrated associations between industrial emissions and cancer outcomes [38–40]. Our study aimed to examine the carcinogenic impact and disparities of living in municipalities with reported industrial pollution in Puerto Rico. Understanding these patterns will help prioritize further epidemiological and environmental research, as well as public health interventions, and inform policy changes to mitigate risks in high-risk populations.

MATERIALS AND METHODS

Study design, study population, and outcome data

An ecological study design was employed to analyze the association between TRI exposure and cancer rates in Puerto Rico using data from the Incidence Case File of the Puerto Rico Central Cancer Registry (PRCCR). PRCCR, a population-based registry, is responsible for collecting, analyzing, and publishing information on all cancer cases diagnosed and/or treated in Puerto Rico, meeting the standards established by the National Program of Central Cancer Registries and the Centers for Disease Control and Prevention. The PRCCR data

includes individual-level characteristics, such as age, sex, and municipality of residence at the time of diagnosis. The study population consisted of all cancer patients diagnosed with invasive primary cancer between January 2018-December 2022, who were residents of Puerto Rico at the time of diagnosis. Cancer cases were coded according to the third edition of the International Classification of Diseases for Oncology (ICD-O-3) [41]. It is worth noting that both Hurricane María and the COVID-19 pandemic disrupted health services, causing delays and reductions in cancer detection, diagnosis, and reporting to PRCCR [42]. This may have contributed to the decrease in incidence rates for most municipalities in Puerto Rico in 2020 [6]. This study was approved by the Institutional Review Board of the Comprehensive Cancer Center of the University of Puerto Rico (#2024-06-142).

Exposure data

TRI data were gathered from the EPA's TRI Basic Data Files inventory, which is available online. The TRI was introduced in 1986 under the Emergency Planning and Community Right-to-Know Act (EPCRA) and requires many industry sectors to report on the storage, use, and release of specific chemicals into the environment [43]. An industrial facility is required to report to the TRI if it is included in a TRI-covered North American Industry Classification System code, has ten or more full-time employees equivalents, and either uses or manufactures more than a threshold level of a listed substance that cause cancer, chronic human health effects, significant adverse acute human health effects and/or significant adverse environmental effects [34]. Smaller facilities and those that manufacture or use amounts of a chemical below threshold levels annually are not required to report [43]. These reports are based on measurements conducted by facilities and submitted voluntarily [34]. These TRI data were used to identify exposed municipalities in Puerto Rico, defined as municipalities with facilities that reported on-site emissions over 0 pounds to the TRI at least once during the 15 years from 2006 to 2020. By including only facilities that reported at least one year of on-site emissions, we reduced the bias of including facilities that reported zero emissions or blank data during the 15 years, as the reasons are unclear and may include non-applicable release pathways or pre-mandatory reporting practices [34]. We analyzed data from industries reporting on-site because we wanted to consider chemicals released directly to air, surface water, and land within the municipality where cancer cases were diagnosed. We did not use total reported emissions because they include both on-site and off-site releases, which could misrepresent exposure at the municipal level [34]. We identified two initial categories of municipalities: (1) contaminated, defined as having at least one on-site release over the period; and (2) non-contaminated, defined as having no reports over the period. An additional classification was created based on the frequency of reported emissions, where municipalities were divided into three categories: [1] no on-site TRI reporting for the study period, (2) intermittent on-site emissions over 0 pounds reported from 1 to 14 years of the 15 years, and (3) continuous on-site emissions over 0 pounds reported for all years of the study period (15 years).

Statistical analysis

To estimate the cancer risk between non-exposed and exposed municipalities, we calculated the age-standardized incidence (ASI) with 95% confidence intervals using the direct method and the 2000 PR standard population (19 age groups) for 2018–2022. We then estimated

the age-standardized incidence relative risk (RR=ASI of contaminated areas/ASI of non-contaminated areas) with 95% confidence intervals (95%CI) from 2018 to 2022. These RRs were calculated for the total cancer (all cases) and specific cancer types included in the PRCCR. Analyses were performed overall (total population) and stratified by sex. This analysis was repeated for the exposure variable with three categories to estimate the cancer risk between municipalities with no on-site emissions reported during the study period, intermittent on-site emissions (contaminated), and continuous on-site emissions (highly contaminated). All analyses were conducted using SEER*Stat v8.4.4.

RESULTS

Risk of cancer in contaminated areas

A total of 160 facilities with unique identification numbers (TRIFD) released more than 0 pounds onsite during the study period (Figure 1). Between 2018–2022, 80,179 invasive cancer cases were diagnosed in Puerto Rico: 38,201 (47.6%) among females and 41,978 (52.4%) among males. Of these, 61,446 (77%) resided in municipalities classified as contaminated based on the presence of at least one TRI facility that reported on-site emissions at least once between 2006–2020. Figure 2 shows the age-adjusted cancer rate for all the cancers from 2018 to 2022. For all cancer types, we observed a significant 7% excess risk among residents of contaminated municipalities compared with those in non-contaminated municipalities (RR=1.07, 95%CI:1.05–1.09, p<0.0001). When stratified by sex, the risk remained elevated in both females and males. Specifically, females had a 5% increased risk (RR=1.05, 95%CI:1.02–1.07, p=0.0004), while males residing in contaminated municipalities exhibited a 10% increased risk (RR=1.10, 95%CI:1.07–1.12, p< 0.0001). The results are presented in Table 1 and Table 2.

Overall, specific cancer types showed an increased risk (Table 1). Those living in contaminated municipalities had a statistically significant increased risk of breast, kidney, and renal pelvis, lung and bronchus, non-Hodgkin lymphoma, and pancreatic cancers, compared to those living in non-contaminated municipalities.

Among females living in contaminated municipalities, significant differences were observed for the three types of cancers (Table 2). An increased risk of breast cancer and non-Hodgkin lymphoma and a lower risk of stomach cancer were observed. In contrast, seven different cancer types were statistically significant for males residing in contaminated municipalities compared to those residing in non-contaminated municipalities (Table 2). Increased risk for kidney and renal pelvis cancer, liver and intrahepatic bile duct cancer, lung and bronchus cancer, non-Hodgkin lymphoma, pancreas and prostate cancer, and lower risk for acute myeloid leukemia were observed for males living in contaminated municipalities, compared to those living in non-contaminated municipalities.

Risk of cancer based on the frequency of on-site reported emissions

Of the 77% of cancer patients (n=61,446) who lived in municipalities with a TRI facility between 2006 and 2020, 15% (12,037) lived in municipalities with reported intermittent on-site emissions (contaminated), and 62% (49,409) in municipalities with reported continuous

on-site emissions (highly contaminated). When stratifying by the frequency of emissions and comparing with non-contaminated municipalities, notable patterns were observed, with a significant excess risk observed particularly in contaminated municipalities (Table 3). The results showed an 8% increased risk for all cancer sites among residents in areas with continuous on-site toxic emissions (RR=1.08, 95%CI:1.06–1.10, p<0.0001) compared with those in non-contaminated municipalities. When stratified by sex, the risk remained elevated in both females and males. Females residing in areas with reported intermittent on-site toxic releases exhibited a 2% increased risk (RR=1.02, 95%CI: 0.99–1.06, p=0.25), while females residing in municipalities with reported continuous on-site releases had a 5% increased risk (RR=1.05, 95%CI:1.03–1.08, p<0.0001) for all cancer sites, compared with females residing in non-contaminated municipalities. Males residing in municipalities with reported intermittent on-site releases showed a 1% increased risk (RR=1.01, 95%CI:0.98–1.05, p=0.50), while those residing in municipalities with continuous reports had a 12% increased risk (RR=1.12, 95%CI:1.09–1.15, p<0.0001) for all cancer sites, compared with males residing in non-contaminated municipalities.

Significant differences in cancer occurrence by the frequency of TRI-reported emissions were also observed by sex (Table 4). In females, a significantly increased risk for breast cancer, lung and bronchus cancer, and non-Hodgkin lymphoma was observed in those residing in municipalities with continuous on-site toxic emissions, compared to those residing in municipalities without on-site emissions. Females who resided in municipalities with reported intermittent on-site releases had a significantly increased risk for cancer in the esophagus and a decreased risk of stomach cancer compared to with those residing in non-contaminated municipalities. Several specific cancer types among females showed a higher risk with an increased frequency of on-site reported emissions, although none were statistically significant (Table 4). These included cervix uteri, chronic lymphocytic leukemia, chronic myeloid leukemia, corpus and uterus, myeloma, oral cavity and pharynx, ovary, vagina, and vulva.

Among males, several cancers were also associated with living in contaminated and highly contaminated municipalities (Table 4). The analysis revealed a significant increase in cancer risk for the anus, anal canal and anorectum, kidney and renal pelvis, liver and intrahepatic bile duct, lung and bronchus, prostate, and non-Hodgkin lymphoma, among men who resided in municipalities with continuous onsite emissions compared to those living in non-contaminated municipalities. Similarly, males had a significant 23% increased risk of pancreatic cancer (RR=1.23, 95%CI: 1.00–1.51, p=0.049) in municipalities with intermittent on-site emissions, and an 18% increased risk of pancreatic cancer (RR=1.18, 95%CI: 1.01–1.38, p=0.04) in municipalities with reported continuous on-site emissions, compared to those residing in non-contaminated municipalities. A decreased risk of acute myeloid leukemia was observed among males living in municipalities with continuous toxic on-site releases, compared to those residing in non-contaminated municipalities.

DISCUSSION

To our knowledge, this is the first ecological study in Puerto Rico to examine how contaminated and non-contaminated municipalities relate to cancer risk by evaluating

two exposure types: the presence of industries and the frequency of pollutants released into the environment. Our findings suggest a positive trend with frequently contaminated municipalities having the highest increased risk of cancer. In our primary analysis, we found that residing in municipalities with a TRI facility reporting on-site toxic releases was linked to an increased risk for all sites and several specific cancer types when stratifying by sex (i.e., breast, kidney and renal pelvis, lung and bronchus, non-Hodgkin lymphoma, and pancreas) compared to municipalities without a TRI facility between 2006–2020.

Breast and prostate cancers, in females and males, respectively, are the most incident in Puerto Rico [6], the US [44], and among the top three cancer types worldwide [45]. Our study identified several important findings for these cancer types, where people who live in municipalities with a TRI facility had a significantly increased risk of breast and prostate cancers in females and males, respectively. These findings are consistent with previous scientific literature reporting associations between industrial pollutants and breast cancer [46–47] as well as prostate cancer [48–49]. A prior study in Canada found an increased risk of breast cancer among residents living in proximity to industrial plants [50], while a prospective cohort study in the US found that breast cancer incidence was associated with certain industrial carcinogens [51]. Recent studies have associated toxic environmental pollutants, particularly endocrine-disrupting chemicals (EDC) such as dioxins and phthalates, with breast cancer [52]. According to the TRI, industries in Puerto Rico have emitted multiple known or suspected EDCs throughout the archipelago, including dioxin, dioxin-like compounds, polycyclic aromatic compounds, benzene, formaldehyde, lead, and ethylene oxide. When considering the frequency of emissions, we identified that the risk for both breast and prostate cancers was significantly higher when on-site emissions were reported for 15 consecutive years compared with intermittent releases from 1 to 14 years. This suggests that longer exposure can lead to greater risk.

Our findings also contribute to the existing literature by highlighting the positive association between lung cancer and environmental pollution. Lung cancer is the most common cancer worldwide [53], and in the US, it is the leading cause of cancer-related death in both sexes [44]. While smoking is the primary risk factor, living in polluted areas also increases this risk [54]. Our study found that residents of contaminated or highly contaminated municipalities have an increased risk of lung and bronchus cancer. Specifically, we found a significantly increased risk of lung and bronchus cancer in males based on the presence of a TRI; females showed an increase, but this was not statistically significant. However, when analyzing the frequency of released emissions between 2006–2020, a significantly higher risk of lung cancer was observed with continuous emissions than with intermittent emissions. This finding emphasizes the importance of studying exposure patterns. For instance, 11 chemicals classified as carcinogenic by the OSHA in the TRI database were continuously released between 2006–2020 in Puerto Rico.

Interestingly, our study showed a reduced risk of two cancer types, acute myeloid leukemia and stomach cancer, in both analyses of contaminated areas, with a lower risk in males living in municipalities with TRI facilities and in municipalities with continuous on-site emissions. These results differ from the American Cancer Society data [55], where acute myeloid leukemia is more common in men than in women. In contrast, females had a

less significant risk of stomach cancer in municipalities with toxic emissions and those with continuous toxic releases. While further research is needed to elucidate these findings, treatment with certain chemotherapy drugs and infections with *Helicobacter pylori* are important risk factors for acute myeloid leukemia and stomach cancer, respectively [56–59]. Previous studies have reported that *H. pylori* infection is common among Hispanics living in Puerto Rico, with a seroprevalence of 33% [57], which should be considered in future studies. In addition, long-term chemical exposure, such as benzene, reported in seven municipalities (Aguadilla, Bayamón, Carolina, Guayama, Guaynabo, Peñuelas, and Yabucoa) may explain some of the findings. However, the exposure duration requires further study, as there may be confounding effects that were not considered in this study. Furthermore, smoking remains the sole confirmed lifestyle-related risk factor for acute myeloid leukemia [56].

Previous research has shown that cancer is not distributed equally and that the burden of environmental pollution disproportionally affects Hispanic/Latino populations [8]. In the US, individuals with limited education or living in poverty have a higher risk of exposure to carcinogenic air emissions from industrial facilities [10]. According to the US Census Bureau (2022: ACS 5-Year Estimates), 28.3% of people in Puerto Rico have a bachelor's degree or higher educational level and a median household income (US dollars) of $24,002, with 42.2% of people living below the poverty level, which is higher than in the US. Moreover, Puerto Rico has experienced a significant increase in more frequent and/or intense extreme weather events in recent decades [60–62], which likely exacerbates the degree of human exposure to both industrial and non-industrial pollution [63], resulting in higher morbidity and mortality [64]. Events such as Hurricane María in 2017 mobilized emerging and anthropogenic pollutants in the environment, damaging the water infrastructure and increasing contaminant levels, including pesticides and metals such as copper, strontium, and vanadium, with significant differences in both chemical and toxicity levels [65]. Other non-TRI-related pollution sources, such as Superfund sites [32], landfills and waste management [66], traffic-related contamination [67], and poor drinking water quality [68], may also contribute to the cancer risk in Puerto Rico. Therefore, further research is necessary to comprehend the effects of social and environmental determinants of health on cancer incidence and environmental exposure within this population, including the intersection of extreme weather events and exposure to pollutants tracked and not tracked by TRI on cancer risk.

Estimating the health impact of contaminated sites, particularly those resulting from industrial emissions, is complex. This study had several limitations, mainly due to its ecological design. We lacked individual environmental exposure data, and the exposures likely varied among individuals and even within municipalities. Additionally, we were unable to adjust for individual cancer risk factors or potential confounding variables, which may have biased the results. Despite the completeness of the data collected by the PRCCR database, we only had access to cancer incidence data at the municipal level; therefore, we were unable to assess the correlations of proximity to TRI-reporting facilities. This led to a simplified assumption that all people in a municipality had equal exposure during the 15-year exposure period. An important consideration when interpreting the results of this analysis is the potential for an ecological fallacy. This assumption

overlooks the interconnected nature of pollutant transport in ecosystems [69–70]. Thus, studies incorporating location-specific data and spatial analysis methods could contribute to a better understanding of environmental effects on cancer risk. Further studies should also consider varying latency periods for each cancer type.

The limitations of the TRI data were previously described in the Methods section. In brief, (1) smaller facilities and smaller chemical uses are not reported but may still release substantial levels of pollutants [71]; (2) there is evidence that some facilities underreport TRI emissions, resulting in systematic measurement errors in the database [72]; and (3) the TRI covers many but not all industry sectors; therefore, substances that may be relevant to cancer development may not be included. To address bias related to exposure misclassification concerning residential mobility, we consulted the US Census ACS 5-Year Estimates for 2018 (RRID: SCR_011587), which showed that 91% of the population lived in the same household as the previous year, 4% moved within the same municipality, 2% moved to a different municipality, and 3% moved to the US. This trend persisted in the ACS 5-Year Estimates for 2022. This suggests that the misclassification bias is likely to be minimal. Despite these limitations, our findings provide a basis for future epidemiological and environmental research.

This study contributes to the discussion that the presence of polluting industries may increase the risk of cancer, highlighting a significant association between living in municipalities with industrial pollution and increased risk of cancer. Continued surveillance and environmental health assessments are necessary to address the long-term health impact of industrial pollution. Additionally, cancer screening programs can be reinforced in municipalities with TRI-reporting facilities.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Data availability

The TRI data used in this study are publicly available on the EPA’s public website: Toxics Release Inventory (TRI) Program | US EPA. The data generated in this study are not publicly available because of information that could compromise patient privacy but are available upon reasonable request from the corresponding author.

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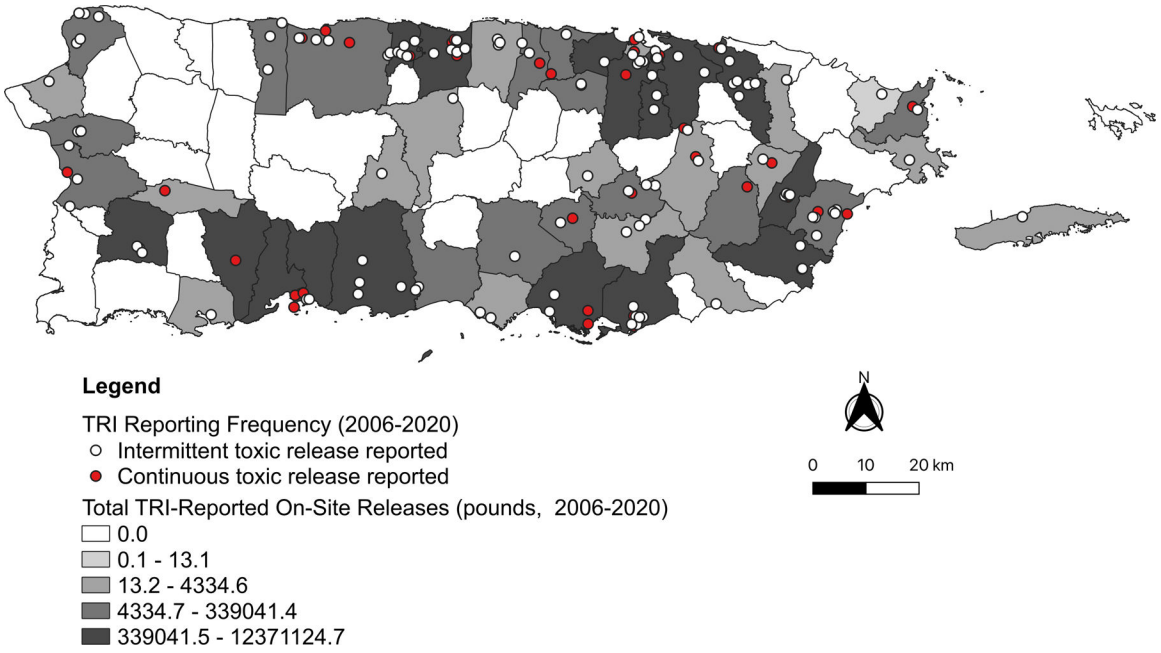

Figure 1: Choropleth map of Puerto Rico showing the total on-site releases reported to the TRI (in pounds) by municipality from 2006 to 2020.

The overlaid points represent the geocoded locations of TRI-reporting facilities from 2006 to 2020. White circles indicate facilities with reported intermittent toxic releases, and red circles indicate facilities with continuous toxic releases reported.

Abbreviations: TRI = Toxic Release Inventory

Note. Total TRI-reported on-site releases were classified using the Equal Count (quantile) method.

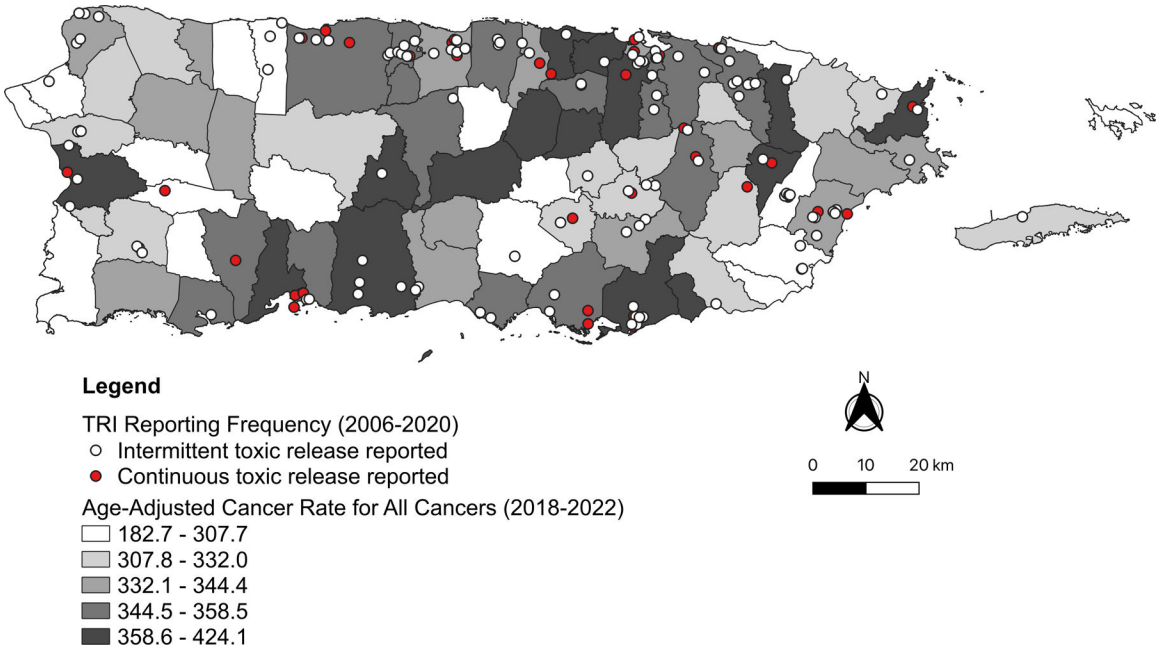

Figure 2: Choropleth map of Puerto Rico showing the age-adjusted cancer rate for all cancers from 2018 to 2022.

The overlaid points represent the geocoded locations of TRI-reporting facilities from 2006 to 2020. White circles indicate facilities with reported intermittent toxic releases, and red circles indicate facilities with continuous toxic releases reported.

Abbreviations: TRI = Toxic Release Inventory

Note. Age-adjusted cancer rates were classified using the equal count (quantile) method.

Table 1

Cancer risk among both sexes in Puerto Rico, based on age-standardized incidence rates (2018–2022) and TRI-reported industrial emissions (2006–2020), categorized as contaminated (reported on-site emissions) and non-contaminated (without reported on-site emissions) municipalities

Cancer Type	Age-Standardized Incidence Rate*		RR (95%CI)**	p-value
	Contaminated	Non-Contaminated		
All Sites	**323.0**	**302.8**	**1.07 (1.05 – 1.09)**	**<0.0001**
Acute Lymphocytic Leukemia	1.5	1.4	1.10 (0.77 – 1.61)	0.66
Acute Myeloid Leukemia	2.3	2.7	0.85 (0.69 – 1.04)	0.12
Anus, Anal Canal and Anorectum	1.6	1.3	1.28 (0.98 – 1.68)	0.08
Brain and Other Nervous System	4.0	3.7	1.08 (0.90 – 1.30)	0.43
Breast	**50.9**	**47.4**	**1.07 (1.03 – 1.12)**	**0.002**
Chronic Lymphocytic Leukemia	2.2	2.1	1.06 (0.87 – 1.30)	0.62
Chronic Myeloid Leukemia	1.6	1.5	1.13 (0.87 – 1.49)	0.40
Colon and Rectum	33.8	32.8	1.03 (0.98 – 1.09)	0.24
Esophagus	2.6	2.4	1.08 (0.90 – 1.30)	0.43
Hodgkin Lymphoma	2.4	2.2	1.09 (0.85 – 1.40)	0.55
Kidney and Renal Pelvis	**8.6**	**7.7**	**1.13 (1.01 – 1.26)**	**0.04**
Leukemia	9.1	8.8	1.04 (0.93 – 1.16)	0.57
Liver and Intrahepatic Bile Duct	7.4	6.8	1.09 (0.98 – 1.22)	0.12
Lung and Bronchus	**13.5**	**12.1**	**1.12 (1.03 – 1.21)**	**0.01**
Melanoma of the Skin	2.9	3.3	0.85 (0.72 – 1.02)	0.09
Myeloma	5.7	5.3	1.06 (0.94 – 1.20)	0.38
Non-Hodgkin Lymphoma	**12.6**	**10.7**	**1.18 (1.07 – 1.29)**	**0.0004**
Oral Cavity and Pharynx	7.9	7.4	1.08 (0.97 – 1.21)	0.18
Pancreas	**7.6**	**6.8**	**1.13 (1.01 – 1.26)**	**0.03**
Stomach	5.6	6.1	0.92 (0.82 – 1.04)	0.18
Thyroid	20.8	21.2	0.98 (0.91 – 1.06)	0.59
Urinary Bladder	8.6	8.3	1.03 (0.94 – 1.14)	0.55

Note.

*Rates are per 100,000 and age-standardized to the 2000 PR Std Population;

**Confidence intervals (Tiwari mod) are 95% for rates and ratios.

Table 2

Cancer risk by sex in Puerto Rico, based on age-standardized incidence rates (2018–2022) and TRI-reported industrial emissions (2006–2020), categorized as contaminated (reported on-site emissions) and non-contaminated (without reported on-site emissions) municipalities

Cancer Type	Female				Male			
	Age-Standardized Incidence Rate*		RR (95%CI)**	p-value	Age-Standardized Incidence Rate*		RR (95%CI)**	p-value
	TRI reported	No TRI reported			TRI reported	No TRI reported		
All Sites	**295.6**	**282.4**	**1.05 (1.02 – 1.07)**	**0.0004**	**362.1**	**330.2**	**1.10 (1.07 – 1.12)**	**<0.0001**
Acute Lymphocytic Leukemia	1.7	1.4	1.25 (0.75 – 2.17)	0.44	1.3	1.4	0.95 (0.57 – 1.66)	0.92
Acute Myeloid Leukemia	2.3	2.1	1.05 (0.76 – 1.48)	0.84	**2.4**	**3.4**	**0.71 (0.54 – 0.93)**	**0.01**
Anus, Anal Canal and Anorectum	1.8	1.6	1.14 (0.81 – 1.61)	0.54	1.4	0.9	1.53 (0.96 – 2.49)	0.08
Brain and Other Nervous System	3.6	3.1	1.18 (0.88 – 1.58)	0.29	4.5	4.5	1.00 (0.79 – 1.28)	1.00
Breast	**92.2**	**88.0**	**1.05 (1.00 – 1.10)**	**0.04**	0.9	0.8	1.16 (0.70 – 1.95)	0.71
Cervix Uteri	10.2	10.0	1.02 (0.87 – 1.19)	0.88	-	-	-	-
Chronic Lymphocytic Leukemia	1.5	1.4	1.03 (0.74 – 1.45)	0.99	3.1	2.8	1.10 (0.85 – 1.44)	0.51
Chronic Myeloid Leukemia	1.2	1.1	1.11 (0.71 – 1.76)	0.76	2.2	1.9	1.16 (0.83 – 1.66)	0.44
Colon and Rectum	28.4	27.1	1.05 (0.97 – 1.13)	0.27	40.6	39.3	1.03 (0.96 – 1.11)	0.40
Corpus and Uterus, NOS	30.1	30.4	0.99 (0.92 – 1.07)	0.85	-	-	-	-
Esophagus	0.9	0.6	1.67 (1.00 – 2.77)	0.052	4.6	4.6	1.02 (0.83 – 1.25)	0.93
Hodgkin Lymphoma	2.0	1.5	1.33 (0.89 – 2.06)	0.18	2.8	2.9	0.96 (0.70 – 1.33)	0.84
Kidney and Renal Pelvis	5.3	5.5	0.95 (0.79 – 1.16)	0.65	**12.8**	**10.3**	**1.25 (1.09 – 1.43)**	**0.001**
Leukemia	7.8	7.0	1.10 (0.92 – 1.33)	0.30	10.9	10.9	1.00 (0.86 – 1.16)	1.00
Liver and Intrahepatic Bile Duct	3.7	3.6	1.02 (0.82 – 1.27)	0.95	**12.0**	**10.5**	**1.14 (1.00 – 1.30)**	**0.04**
Lung and Bronchus	10.1	9.1	1.11 (0.97 – 1.26)	0.12	**17.8**	**15.6**	**1.14 (1.03 – 1.27)**	**0.01**
Melanoma of the Skin	2.2	2.8	0.79 (0.60 – 1.05)	0.11	3.7	4.0	0.92 (0.73 – 1.16)	0.48
Myeloma	4.9	4.6	1.07 (0.88 – 1.29)	0.56	6.6	6.2	1.07 (0.90 – 1.27)	0.49
Non-Hodgkin Lymphoma	**10.7**	**9.0**	**1.18 (1.03 – 1.36)**	**0.02**	**15.0**	**12.8**	**1.18 (1.04 – 1.33)**	**0.01**
Oral Cavity and Pharynx	4.3	4.3	1.02 (0.83 – 1.26)	0.93	12.5	11.0	1.14 (1.00 – 1.30)	0.06
Ovary	7.5	6.6	1.14 (0.96 – 1.37)	0.14	-	-	-	-
Pancreas	6.5	6.0	1.07 (0.91 – 1.26)	0.42	**9.1**	**7.6**	**1.19 (1.02 – 1.39)**	**0.02**
Penis	-	-	-	-	1.9	2.2	0.88 (0.65 – 1.19)	0.43
Prostate	-	-	-	-	**137.1**	**119.7**	**1.15 (1.10 – 1.19)**	**<0.0001**

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Cancer Type	Female				Male			
	Age-Standardized Incidence Rate*		RR (95%CI)**	p-value	Age-Standardized Incidence Rate*		RR (95%CI)**	p-value
	TRI reported	No TRI reported			TRI reported	No TRI reported		
Stomach	**4.6**	**5.6**	**0.83 (0.69 – 0.99)**	**0.04**	6.8	6.7	1.02 (0.87 – 1.21)	0.86
Testis	-	-	-	-	5.3	6.5	0.82 (0.65 – 1.02)	0.08
Thyroid	31.4	32.8	0.96 (0.88 – 1.04)	0.32	9.0	8.8	1.02 (0.87 – 1.21)	0.84
Urinary Bladder	3.8	3.8	0.99 (0.81 – 1.21)	0.99	14.8	13.8	1.07 (0.96 – 1.19)	0.25
Vagina	1.0	0.9	1.11 (0.69 – 1.81)	0.79	-	-	-	-
Vulva	1.3	1.1	1.11 (0.76 – 1.63)	0.71	-	-	-	-

Note.

*Rates are per 100,000 and age-standardized to the 2000 PR Std Population;

**Confidence intervals (Tiwari mod) are 95% for rates and ratios.

Table 3

Cancer risk among both sexes in Puerto Rico, based on age-standardized incidence rates (2018–2022) and the frequency of TRI-reported industrial emissions (2006–2020), categorized as: non-contaminated (no on-site emissions), contaminated (intermittent on-site emissions), and highly contaminated (continuous on-site emissions) municipalities

Cancer Type	TRI Reporting	Age-Standardized Incidence Rate*	RR (95%CI)**	P-value
All Sites	None	302.8	-	-
	Intermittent	308.4	1.02 (0.99 – 1.04)	0.14
	Continuous	**326.9**	**1.08 (1.06 – 1.10)**	**<0.0001**
Acute Lymphocytic Leukemia	None	1.4	-	-
	Intermittent	1.8	1.30 (0.78 – 2.13)	0.33
	Continuous	1.4	1.04 (0.72 – 1.55)	0.88
Acute Myeloid Leukemia	None	2.7	-	-
	Intermittent	2.5	0.93 (0.69 – 1.25)	0.69
	Continuous	2.2	0.82 (0.66 – 1.02)	0.08
Anus, Anal Canal and Anorectum	None	1.3	-	-
	Intermittent	1.5	1.16 (0.80 – 1.69)	0.48
	Continuous	1.7	1.31 (0.99 – 1.73)	0.06
Brain and Other Nervous System	None	3.7	-	-
	Intermittent	4.4	1.18 (0.91 – 1.51)	0.23
	Continuous	3.9	1.06 (0.88 – 1.28)	0.60
Breast	None	47.4	-	-
	Intermittent	47.5	1.00 (0.94 – 1.06)	1.00
	Continuous	**51.7**	**1.09 (1.04 – 1.14)**	**0.0002**
Chronic Lymphocytic Leukemia	None	2.1	-	-
	Intermittent	1.9	0.93 (0.69 – 1.25)	0.72
	Continuous	2.3	1.10 (0.89 – 1.36)	0.41
Chronic Myeloid Leukemia	None	1.5	-	-
	Intermittent	1.3	0.87 (0.57 – 1.30)	0.56

Cancer Type	TRI Reporting	Age-Standardized Incidence Rate*	RR (95%CI)**	P-value
	Continuous	1.7	1.20 (0.91 – 1.59)	0.21
Colon and Rectum	None	32.8	-	-
	Intermittent	34.6	1.06 (0.98 – 1.13)	0.15
	Continuous	33.6	1.03 (0.97 – 1.08)	0.37
Esophagus	None	2.4	-	-
	Intermittent	2.6	1.11 (0.86 – 1.43)	0.46
	Continuous	2.6	1.08 (0.89 – 1.30)	0.49
Hodgkin Lymphoma	None	2.2	-	-
	Intermittent	2.6	1.20 (0.85 – 1.68)	0.31
	Continuous	2.3	1.06 (0.82 – 1.38)	0.71
Kidney and Renal Pelvis	None	7.7	-	-
	Intermittent	8.4	1.10 (0.94 – 1.28)	0.24
	Continuous	**8.7**	**1.13 (1.01 – 1.27)**	**0.03**
Leukemia	None	8.8	-	-
	Intermittent	9.1	1.03 (0.88 – 1.21)	0.74
	Continuous	9.1	1.04 (0.92 – 1.17)	0.55
Liver and Intrahepatic Bile Duct	None	6.8	-	-
	Intermittent	7.2	1.07 (0.92 – 1.25)	0.40
	Continuous	7.4	1.10 (0.98 – 1.23)	0.11
Lung and Bronchus	None	12.1	-	-
	Intermittent	11.8	0.98 (0.87 – 1.10)	0.77
	Continuous	**13.9**	**1.15 (1.06 – 1.25)**	**0.0006**
Melanoma of the Skin	None	3.3	-	-
	Intermittent	2.8	0.85 (0.65 – 1.10)	0.22
	Continuous	2.9	0.86 (0.71 – 1.03)	0.10
Myeloma	None	5.3	-	-
	Intermittent	5.3	0.99 (0.82 – 1.18)	0.93

Cancer Type	TRI Reporting	Age-Standardized Incidence Rate*	RR (95%CI)**	P-value
	Continuous	5.8	1.08 (0.95 – 1.23)	0.26
	None	10.7	-	-
Non-Hodgkin Lymphoma	Intermittent	11.8	1.10 (0.97 – 1.25)	0.15
	Continuous	**12.8**	**1.20 (1.09 – 1.31)**	**<0.0001**
	None	7.4	-	-
Oral Cavity and Pharynx	Intermittent	7.8	1.06 (0.91 – 1.24)	0.46
	Continuous	8.0	1.08 (0.97 – 1.22)	0.17
	None	6.8		
Pancreas	**Intermittent**	**7.9**	**1.17 (1.01 – 1.36)**	**0.04**
	Continuous	7.6	1.11 (1.00 – 1.25)	0.06
	None	6.1	-	-
Stomach	Intermittent	5.8	0.95 (0.81 – 1.13)	0.63
	Continuous	5.5	0.91 (0.81 – 1.03)	0.16
	None	21.2	-	-
Thyroid	Intermittent	20.5	0.97 (0.87 – 1.08)	0.56
	Continuous	20.8	0.98 (0.91 – 1.06)	0.65
	None	8.3	-	-
Urinary Bladder	Intermittent	8.2	0.99 (0.86 – 1.13)	0.88
	Continuous	8.7	1.04 (0.94 – 1.15)	0.44

Note.

*Rates are per 100,000 and age-standardized to the 2000 PR Std Population;

**Confidence intervals (Tiwari mod) are 95% for rates and ratios.

Table 4

Cancer risk by sex in Puerto Rico, based on age-standardized incidence rates (2018–2022) and the frequency of TRI-reported industrial emissions (2006–2020), categorized as: non-contaminated (no on-site emissions), contaminated (intermittent on-site emissions), and highly contaminated (continuous on-site emissions) municipalities.

Cancer Type	TRI Reporting	Female			Male		
		Age-Standardized Incidence Rate*	RR (95%CI)**	P-value	Age-Standardized Incidence Rate*	RR (95%CI)**	P-value
All Sites	None	282.4	-	-	330.2	-	-
	Intermittent	288.3	1.02 (0.99 – 1.06)	0.25	334.0	1.01 (0.98 – 1.05)	0.50
	Continuous	**297.5**	**1.05 (1.03 – 1.08)**	**<0.0001**	**370.0**	**1.12 (1.09 – 1.15)**	**<0.0001**
Acute Lymphocytic Leukemia	None	1.4	-	-	1.4	-	-
	Intermittent	2.1	1.52 (0.73 – 3.05)	0.28	1.5	1.09 (0.51 – 2.26)	0.91
	Continuous	1.6	1.18 (0.69 – 2.08)	0.61	1.3	0.91 (0.53 – 1.63)	0.81
Acute Myeloid Leukemia	None	2.1	-	-	3.4	-	-
	Intermittent	2.6	1.19 (0.75 – 1.88)	0.50	2.5	0.74 (0.49 – 1.11)	0.16
	Continuous	2.2	1.02 (0.72 – 1.44)	1.00	**2.4**	**0.70 (0.53 – 0.93)**	**0.01**
Anus, Anal Canal and Anorectum	None	1.6	-	-	0.9	-	-
	Intermittent	1.8	1.11 (0.69 – 1.79)	0.76	1.1	1.24 (0.63 – 2.41)	0.62
	Continuous	1.8	1.14 (0.80 – 1.63)	0.54	**1.4**	**1.61 (1.00 – 2.64)**	**0.049**
Brain and Other Nervous System	None	3.1	-	-	4.5	-	-
	Intermittent	4.5	1.46 (1.00 – 2.12)	0.051	4.2	0.94 (0.65 – 1.35)	0.81
	Continuous	3.4	1.11 (0.82 – 1.51)	0.55	4.6	1.02 (0.80 – 1.31)	0.94
Breast	None	88.0	-	-	0.8	-	-
	Intermittent	88.4	1.00 (0.94 – 1.07)	0.90	0.7	0.90 (0.40 – 1.96)	0.98

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Cancer Type	TRI Reporting	Female			Male		
		Age-Standardized Incidence Rate*	RR (95%CI)**	P-value	Age-Standardized Incidence Rate*	RR (95%CI)**	P-value
	Continuous	**93.2**	**1.06 (1.01 – 1.11)**	**0.01**	1.0	1.22 (0.73 – 2.09)	0.55
	None	10.0	-	-	-	-	-
Cervix Uteri	Intermittent	8.5	0.85 (0.68 – 1.06)	0.16	-	-	-
	Continuous	10.6	1.06 (0.91 – 1.25)	0.47	-	-	-
	None	1.4	-	-	2.8	-	-
Chronic Lymphocytic Leukemia	Intermittent	1.4	0.95 (0.57 – 1.57)	1.00	2.6	0.93 (0.64 – 1.36)	0.82
	Continuous	1.5	1.05 (0.74 – 1.49)	0.90	3.3	1.15 (0.88 – 1.51)	0.33
	None	1.1	-	-	1.9	-	-
Chronic Myeloid Leukemia	Intermittent	0.6	0.54 (0.24 – 1.19)	0.15	2.0	1.07 (0.65 – 1.76)	0.87
	Continuous	1.4	1.26 (0.80 – 2.00)	0.37	2.2	1.18 (0.83 – 1.70)	0.40
	None	27.1	-	-	39.3	-	-
Colon and Rectum	Intermittent	29.7	1.09 (0.98 – 1.22)	0.11	40.2	1.02 (0.93 – 1.13)	0.66
	Continuous	28.1	1.03 (0.95 – 1.12)	0.43	40.6	1.03 (0.96 – 1.11)	0.39
	None	30.4	-	-	-	-	-
Corpus and Uterus, NOS	Intermittent	28.9	0.95 (0.85 – 1.06)	0.37	-	-	-
	Continuous	30.5	1.00 (0.93 – 1.09)	0.96	-	-	-
	None	0.6	-	-	4.6	-	-
Esophagus	**Intermittent**	**1.1**	**1.99 (1.02 – 3.80)**	**0.04**	4.4	0.97 (0.72 – 1.28)	0.90
	Continuous	0.9	1.59 (0.93 – 2.67)	0.10	4.7	1.03 (0.84 – 1.27)	0.84

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Cancer Type	TRI Reporting	Female			Male		
		Age-Standardized Incidence Rate*	RR (95%CI)**	P-value	Age-Standardized Incidence Rate*	RR (95%CI)**	P-value
Hodgkin Lymphoma	None	1.5	-	-	2.9	-	-
	Intermittent	2.1	1.42 (0.81 – 2.48)	0.24	3.1	1.08 (0.69 – 1.66)	0.80
	Continuous	2.0	1.31 (0.86 – 2.05)	0.23	2.7	0.93 (0.67 – 1.30)	0.70
Kidney and Renal Pelvis	None	5.5	-	-	10.3	-	-
	Intermittent	5.6	1.02 (0.78 – 1.33)	0.95	11.7	1.14 (0.94 – 1.38)	0.19
	Continuous	5.2	0.94 (0.77 – 1.14)	0.53	**13.1**	**1.28 (1.11 – 1.47)**	**0.0005**
Leukemia	None	7.0	-	-	10.9	-	-
	Intermittent	7.9	1.13 (0.87 – 1.46)	0.39	10.5	0.97 (0.78 – 1.19)	0.79
	Continuous	7.7	1.10 (0.91 – 1.33)	0.33	11.0	1.01 (0.87 – 1.17)	0.95
Liver and Intrahepatic Bile Duct	None	3.6	-	-	10.5	-	-
	Intermittent	4.1	1.12 (0.84 – 1.51)	0.48	11.0	1.05 (0.87 – 1.25)	0.65
	Continuous	3.6	0.99 (0.79 – 1.25)	1.00	**12.3**	**1.17 (1.03 – 1.34)**	**0.02**
Lung and Bronchus	None	9.1	-	-	15.6	-	-
	Intermittent	8.6	0.94 (0.78 – 1.14)	0.59	15.7	1.00 (0.86 – 1.16)	1.00
	Continuous	**10.5**	**1.15 (1.01 – 1.32)**	**0.03**	**18.4**	**1.18 (1.06 – 1.31)**	**0.002**
Melanoma of the Skin	None	2.8	-	-	4.0	-	-
	Intermittent	2.6	0.92 (0.61 – 1.37)	0.77	3.1	0.77 (0.54 – 1.10)	0.17
	Continuous	2.2	0.76 (0.56 – 1.02)	0.07	3.8	0.95 (0.75 – 1.21)	0.74
Myeloma	None	4.6	-	-	6.2	-	-
	Intermittent	4.6	0.98 (0.75 – 1.29)	0.99	6.1	0.99 (0.77 – 1.27)	1.00

Cancer Type	TRI Reporting	Female			Male		
		Age-Standardized Incidence Rate*	RR (95%CI)**	P-value	Age-Standardized Incidence Rate*	RR (95%CI)**	P-value
Non-Hodgkin Lymphoma	Continuous	5.0	1.09 (0.90 – 1.32)	0.44	6.7	1.09 (0.91 – 1.31)	0.37
	None	9.0	-	-	12.8	-	-
	Intermittent	10.4	1.15 (0.95 – 1.39)	0.17	13.5	1.06 (0.89 – 1.26)	0.54
	Continuous	**10.8**	**1.19 (1.03 – 1.37)**	**0.02**	**15.4**	**1.21 (1.07 – 1.37)**	**0.003**
Oral Cavity and Pharynx	None	4.3	-	-	11.0	-	-
	Intermittent	4.1	0.95 (0.70 – 1.29)	0.83	12.3	1.12 (0.93 – 1.34)	0.23
	Continuous	4.4	1.04 (0.84 – 1.28)	0.82	12.5	1.14 (1.00 – 1.31)	0.054
Ovary	None	6.6	-	-	-	-	-
	Intermittent	6.8	1.03 (0.81 – 1.32)	0.84	-	-	-
	Continuous	7.7	1.17 (0.98 – 1.41)	0.09	-	-	-
Pancreas	None	6.0	-	-	7.6	-	-
	Intermittent	6.6	1.10 (0.88 – 1.38)	0.43	**9.4**	**1.23 (1.00 – 1.51)**	**0.049**
	Continuous	6.4	1.06 (0.90 – 1.26)	0.50	**9.0**	**1.18 (1.01 – 1.38)**	**0.04**
Penis	None	-	-	-	2.2	-	-
	Intermittent	-	-	-	2.0	0.89 (0.58 – 1.38)	0.71
	Continuous	-	-	-	1.9	0.87 (0.63 – 1.19)	0.41
Prostate	None	-	-	-	119.7	-	-
	Intermittent	-	-	-	119.4	1.00 (0.95 – 1.05)	0.96
	Continuous	-	-	-	**142.0**	**1.19 (1.14 – 1.23)**	**<0.0001**

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Cancer Type	TRI Reporting	Female			Male		
		Age-Standardized Incidence Rate*	RR (95%CI)**	P-value	Age-Standardized Incidence Rate*	RR (95%CI)**	P-value
Stomach	None	5.6	-	-	6.7	-	-
	Intermittent	5.3	0.95 (0.74 – 1.22)	0.79	6.4	0.95 (0.75 – 1.21)	0.76
	Continuous	**4.4**	**0.80 (0.66 – 0.96)**	**0.01**	7.0	1.04 (0.88 – 1.24)	0.68
Testis	None	-	-	-	6.5	-	-
	Intermittent	-	-	-	5.5	0.85 (0.61 – 1.16)	0.32
	Continuous	-	-	-	5.2	0.81 (0.64 – 1.02)	0.07
Thyroid	None	32.8	-	-	8.8	-	-
	Intermittent	30.5	0.93 (0.82 – 1.05)	0.25	9.6	1.10 (0.87 – 1.38)	0.44
	Continuous	31.6	0.96 (0.88 – 1.05)	0.43	8.8	1.00 (0.84 – 1.19)	1.00
Urinary Bladder	None	3.8	-	-	13.8	-	-
	Intermittent	3.9	1.01 (0.76 – 1.34)	1.00	13.3	0.96 (0.82 – 1.13)	0.69
	Continuous	3.8	0.99 (0.80 – 1.21)	0.95	15.2	1.09 (0.98 – 1.23)	0.12
Vagina	None	0.9	-	-	-	-	-
	Intermittent	0.6	0.71 (0.33 – 1.52)	0.49	-	-	-
	Continuous	1.1	1.21 (0.75 – 1.99)	0.52	-	-	-
Vulva	None	1.1	-	-	-	-	-
	Intermittent	1.1	0.99 (0.56 – 1.73)	1.00	-	-	-
	Continuous	1.3	1.14 (0.77 – 1.68)	0.62	-	-	-

Note.

*Rates are per 100,000 and age-standardized to the 2000 PR Std Population;

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** Confidence intervals (Tiwari mod) are 95% for rates and ratios.