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Descriptive analysis to establish the prevalence of lead-associated chronic conditions among adult public health registry participants in Flint, Michigan: identifying disparities to support focused recovery efforts

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ABSTRACT

Background A population-level trauma, the Flint water crisis (FWC) exposed approximately 140 000 people to lead in water. In response, the Flint Registry (FR) was established by a local university in partnership with the community. Lead exposure has been linked to multiple adult-onset chronic diseases, and addressing the health needs of those exposed requires estimating the prevalence of these conditions. Our objective was to calculate the prevalence of chronic conditions among FR-enrolled adults and compare prevalence to state-wide surveillance estimates.

Methods Data collection for the FR started 4.5 years after the onset of the FWC; this cross-sectional study included participants who completed their enrolment survey December 2018–July 2022. Participants reported if they had ever been diagnosed with 11 chronic conditions. We used crude and age-adjusted prevalence of the 11 chronic conditions and compared them to 2019–2021 Michigan Behavioral Risk Factor Surveillance System (MiBRFSS) estimates.

Results We included 14 274 adult (≥18) participants in this study. Crude and age-adjusted prevalence was higher in FR participants than MiBRFSS estimates for 9 of the 11 chronic conditions, such as kidney disease. Age-adjusted results suggested that 8.1% of participants would have kidney disease if they had the same age distribution as the adult population of Michigan, whereas only 3.4% of the adult population in Michigan has a kidney disease diagnosis. Patterns for males, females, black and white participants were similar to the overall results, though differences between the black FR participants and MiBRFSS estimates were less extreme.

Conclusion The FR is a resource for the Flint community and an example for other communities experiencing mass environmental disruptions. We cannot assert the FWC caused any cases of the health conditions evaluated, however, establishing the prevalence of lead-associated conditions among people exposed to the FWC is needed to prioritise secondary prevention efforts and demonstrate the utility of a university-run registry in response to events like the FWC.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ The Flint water crisis exposed more than 140 000 people to lead and resulted in community trauma. Health implications of the water crisis are still emerging.

WHAT THIS STUDY ADDS

⇒ We used Flint Registry data to estimate the crude and age-adjusted (Michigan) prevalence of 11 chronic conditions reported by 14 274 people exposed to the Flint water crisis and compared them to Michigan prevalence estimates from corresponding Michigan Behavioral Risk Factor Surveillance System waves.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ This work demonstrates the capacity of a community-requested, university-implemented, surveillance system to estimate the prevalence of lead-associated chronic health conditions following a public health crisis.

INTRODUCTION

Flint, Michigan, an urban city in the midwestern USA, experienced a public health crisis when for 18 months residents unknowingly consumed lead-contaminated water. The Flint water crisis (FWC) began on 25 April 2014, when, under the direction of a state-appointed emergency financial manager, Flint's water supply was switched from pretreated water from the Detroit

Water and Sewerage Department's Lake Huron source to locally treated Flint River water.[1 2] The original 1967 contract with Detroit Water and Sewerage Department was born out of a need for a sufficient supply of water to support a then-growing city.[3] Even after a considerable population decline between 1980 and 2000, resulting in a disproportionately large water system for the city with implications for water quality,[4–6] from 2001 to the 2014 water switch the 90th percentile of lead concentrations from routine water sampling remained under 5 µg/L and the occurrence of individual samples exceeding the 15 µg/L action level was rare.[3] After the 2014 return to the Flint River source, the absence of corrosion control treatment resulted in lead from the city's water service lines and premise plumbing leaching into the drinking water,[7–9] exposing an estimated 140 000 people to water lead levels exceeding the federal action level.[1] Along with lead, Flint's water had other contaminants, including *Escherichia coli*, total coliforms, trihalomethanes and *Legionella*, that also have acute and chronic health implications.[3] Flint was 'not the first, the last nor the worst lead-in-water crisis',[10] however, there are no established safe thresholds of lead exposure[11] and US biomonitoring efforts through the National Health and Nutrition Examination Survey demonstrate that adults are still exposed to lead at low levels (median: 0.85 µg/dL in 2018)[12] and lead exposure is still a critical public health problem.

The Agency for Toxic Substances and Disease Registry (ATSDR) comprehensively reviewed the effects of lead exposure on humans in the 2020 Toxicological Profile for Lead and notes that every studied organ system has noted toxicities associated with lead exposure.[11] The review found consistent associations between lead exposure and adverse outcomes for neurological dysfunction like depression, renal disease, cardiovascular conditions, especially elevated blood pressure, and immunological effects that can result in sensitisation and autoimmunity; other conditions that have noted but inconsistent associations included respiratory problems like asthma and chronic obstructive pulmonary disease (COPD), cancer, pain conditions and stroke.[11] A health and environmental injustice instigated by government-made decisions and sustained by government indifference,[13] the FWC can also be characterised as a source of chronic stress and post-traumatic stress disorder (PTSD).[14 15] Chronic stress has been associated with many inflammatory-mediated chronic health conditions.[16] Post-FWC research has identified substantial adult mental health concerns[15 17]; however, a comprehensive evaluation of a broad range of chronic health conditions is limited, and long-term surveillance of chronic health conditions is important for recovery efforts.

In response to the FWC, the CDC funded the Michigan State University College of Human Medicine to create the Flint Registry (FR), a public health surveillance system and secondary prevention resource to connect victims to mitigating health promotion resources.[1] The FR is a surveillance system administered by a university and developed in partnership with the affected community that can serve as a model to other communities that experience mass environmental exposures.[1 18] Surveillance of chronic conditions among adults in the FR informs our understanding of Flint's current health state, provides insight into potential interventions and demonstrates the utility of this surveillance system design. Thus, this study's objective is to estimate the prevalence of chronic health conditions in the FR adult population and compare them to statewide public health surveillance estimates.

METHODS

Setting and participants

This is a cross-sectional analysis of data from FR participants aged 18 years and older who enrolled between the project launch in December 2018 and July 2022. FR eligibility required that a person had lived, worked, attended school/daycare or been in utero in the city of Flint, MI, during the time of the water switch (25 April 2014–15 October 2015). Starting in December 2018, the FR recruited participants through a combination of generalised and targeted strategies. Recruitment approaches included broad advertising, enrolment at local events, partner organisation recruitment and city-wide mailings. Targeted mailings were sent to individuals who met FR eligibility criteria and were part of Michigan Department of Health and Human Services (MDHHS) databases (Childhood Lead Poisoning Prevention Program, Michigan Care Improvement Registry, Medicaid) or were a Hurley Medical Center patient. Phone calls were made to potentially eligible participants. A total of 20 416 individuals (adults and children) consented to participate in the FR through 31 July 2022, and of these, 14 274 were adults at the time of enrolment in the FR (6142 children were not included in this study).

Data sources

Participants completed surveys online (70%), via phone (23%), through the mail (5%) or in person (1%). This analysis uses survey questions about demographics, FWC exposure and health status with a focus on health conditions associated with lead exposure. Michigan Behavioral Risk Factor Surveillance System (MiBRFSS) data for survey years 2019–2021 were obtained from the MDHHS. Age distributions for the Michigan population age 18 and older used for age adjustment of the FR participant prevalence estimates were pulled from the American Community Survey (ACS) 5-year tables 2017–2021 for the total Michigan population and also for female, male, black and white populations.[19–21] To be included in this analysis, participants had to have complete data for age at enrolment and be over 18 years at enrolment. For stratified analyses (gender/race), participants had to have complete data for gender and race.

Primary outcomes

Participants were asked if they had ever been diagnosed by a healthcare provider for 27 health conditions. We

identified 11 chronic conditions that had comparable measures reported in the MiBRFSS between 2019 and 2021 (online supplemental table 1)[22] that have been associated with lead exposure: arthritis/fibromyalgia/lupus/gout, cancer (skin and any other type), asthma, COPD/chronic bronchitis/emphysema, depression, kidney disease, angina, high cholesterol, hypertension, heart attack and stroke. We used only responses that indicated yes or no to each diagnosis; unknown answers were treated as missing. For asthma, we reported both ever diagnosed and if the respondent currently had asthma.

Rationale for the selected chronic conditions

Consistent evidence has shown associations between lead exposure and the following conditions. The ATSDR noted a strong positive association with depression in studies with mean blood lead levels (BLLs) of ≤10 µg/dL.[11] Both the International Agency for Research on Cancer and the ATSDR note the capacity of lead exposure to damage kidneys and to be associated with kidney disease,[11 23] though reduced kidney function may result in higher BLLs due to reduced elimination of lead through urine output.[11] A longitudinal study of chronic kidney disease identified higher risk of chronic kidney disease among participants with BLLs above 33 µg/dL.[24] Hypertension is associated with many chronic disease endpoints, including kidney disease and stroke, and has noted associations with lead exposure measured in both blood and bone (patella and tibia) in cross-sectional and longitudinal research designs.[11 25] The ATSDR found bone lead concentration is positively associated with higher risk of ischaemic heart disease (defined as myocardial infarction or angina pectoris) among men and higher odds of cardiovascular disease among women.[11] Other reviews have identified lead exposure as a risk factor for heart disease, atherosclerosis and stroke.[26–28]

Inconsistent associations have been noted for arthritis and other inflammatory conditions, cancer, asthma and chronic bronchitis and COPD. The strength of evidence for exposure to lead and arthritis, fibromyalgia, lupus and gout is weak with limited evidence finding positive associations of BLLs with arthritis,[29] lupus[30] and gout,[31] but there is a paucity of research about lead exposure and fibromyalgia outcomes. The International Agency for Research on Cancer classified lead as a probable human carcinogen, but much of this work is based on occupational exposure research and is likely dependent on the type of cancer and level of exposure.[11 23] Population-based studies have found null results for BLLs and breast cancer,[32] but population-level evidence of lead exposure and incident cancers is still needed. There is limited evidence for positive associations of BLLs and wheeze and inverse associations with lung function,[33] and BLLs were positively correlated with bronchial responsiveness.[34] Few studies examine the risk of chronic bronchitis and other obstructive lung diseases in relation to lead exposure and most work previously focused on particulate matter in air pollution.[11 35]

Stratification variables

Because nearly 70% of respondents reported their gender as female and 60% reported their race as black, we included analyses stratified by gender and race. In the total population, gender could be reported as male, female, unknown or other, and participants could select multiple race categories. We categorised race responses as black only, white only, any other single race or multiracial. We also stratified by race for those who selected only black or white. In gender-stratified analysis, we only included participants who reported male or female genders; sample sizes for unknown and others were too small to report.

Population descriptive variables

Self-reported survey data used to describe the FR population included: age at survey completion, gender, number of months residing in Flint during the FWC, exposure to contaminated drinking water frequency, race, annual household income, smoking status, time since last routine check-up with a primary care physician, general health status and body mass index. The category 'unknown or missing' was included as a valid response for all descriptive variables.

Statistical analysis

We used median (Q1, Q3) to describe participant age. Body mass index was categorised as unknown, <25 kg/m^2, 25 to <30 kg/m^2 and ≥30 kg/m^2. Frequencies (percentages) were used to describe categorical characteristics of the population and the 11 health outcomes. For the health outcomes, we estimated crude percentages and age-adjusted prevalence (adjusted to Michigan age distribution 18 years and older obtained from the ACS 2017–2021 estimates) of ever being diagnosed with each condition and stratified by age group. We also calculated the percentage of diagnoses made after April 2014, and the prevalence of diagnosis among those at risk after April 2014, excluding individuals previously diagnosed with each condition. Complete data for health conditions were not required and we treated unknown responses as missing; the denominators vary for each outcome. Data reported by the MiBRFSS from 2019 to 2021 were used as estimates of prevalence of ever-diagnosed conditions in Michigan. We stratified by gender and by race and compared the prevalence of ever-diagnosed for the 11 health conditions to gender-stratified and race-stratified MiBRFSS estimates for Michigan. Gender-stratified and race-stratified, age-adjusted estimates were also adjusted to the corresponding Michigan age distribution. The age distributions used for gender-specific age adjustments were estimated from the ACS 2017–2021 for males and females separately and black and white participants separately. We reported 95% CIs for age-adjusted prevalence estimates and MiBRFSS estimates (reported in parentheses after point estimates). We used SAS V.9.4 (SAS Institute) PROC FREQ and PROC MEANS, and RStudio[36] with the epitools package.[37]

Table 1 Descriptive characteristics of the Flint Registry adult population

Characteristic	Category	Total percentage	Female percentage	Male percentage	Black percentage	White percentage
n		14 274	9748	4455	8497	4493
Age	Median (Q1, Q3)	47.5 (33.4, 60.2)	46.3 (33.2, 59.6)	49.8 (34.1, 61.3)	47.6 (32.6, 60.7)	48.5 (35.4, 59.9)
Gender	Female	68.3			69.1	66.8
	Male	31.2			30.7	32.7
	Other/unknown	0.4			0.3	0.6
Race	White	31.5	30.8	32.9		
	Black	59.5	60.2	58.5		
	Other	2.5	2.4	2.8		
	Multiracial	4.9	5.1	4.4		
	Unknown	1.6	1.6	1.4		
Origin	Hispanic	3.5	3.6	3.5	0.8	4.3
	Non-Hispanic	95.3	95.3	95.5	98.3	95.0
	Unknown	1.2	1.2	1.0	0.9	0.7
Income	Less than US$25 000 per year	56.3	56.8	55.5	59.6	49.7
	US$25 000–US$49 999 per year	21.2	21.7	20.3	21.0	22.1
	US$50 000 or higher	13.3	12.9	13.9	9.5	21.2
	Unknown	9.2	8.5	10.3	9.9	7.1
Lived in Flint during FWC	Entire 18 months	80.5	79.0	84.0	86.1	70.4
	Less than 18 months	8.8	9.3	7.7	6.9	11.9
	Did not live in Flint	8.4	9.4	6.3	4.8	15.4
	Unknown	2.3	2.4	2.0	2.2	2.3
Exposed to Flint water via drinking	Yes	88.6	88.1	89.9	88.6	89.0
	No	6.8	7.0	6.3	6.8	6.8
	Unknown	4.6	4.9	3.8	4.6	4.2
Last routine check-up	Within last 12 months	76.8	79.1	71.9	81.0	70.5
	1–2 years ago	11.4	10.9	12.4	10.1	13.1
	2–5 years ago	5.6	4.9	7.1	4.1	8.1
	5 or more years ago/never	3.7	2.4	5.2	1.9	5.5
	Unknown	3.0	2.7	3.4	2.8	2.8
BMI	Less than 25	22.5	20.2	27.5	21.0	24.4
	25–29.9	25.6	23.0	31.4	26.1	24.9
	30 and higher	46.6	51.7	36.0	46.7	47.4
	Unknown	5.3	5.3	5.1	6.2	3.3
Smoking	Daily	24.7	23.6	27.2	21.2	31.2
	Less than daily	6.5	5.7	8.0	7.6	4.4
	Not at all	67.9	69.7	63.9	70.2	63.8
	Unknown	1.0	1.0	0.9	1.1	0.7

Unknown categories include both answers of 'unknown' and missing data. Percentages may not add to 100% because of rounding.
BMI, body mass index; FWC, Flint water crisis.

RESULTS

As of 31 July 2022, the FR had enrolled 14 274 adult participants, 68.3% of whom reported their gender as female (table 1). The median age of the total group was 47.5 (Q1, Q3: 33.4, 60.2) years. Female participants had a slightly younger median age (46.3; Q1, Q3: 33.2, 59.6) than males (49.8; Q1, Q3: 34.1, 61.3). Most of the participants reported their race as black, and almost 90% reported

drinking unfiltered Flint tap water during the switch. Total cohort distributions of the population description variables were similar to gender-stratified distributions, with the exception of time living in Flint (total: 80.5%, female: 79.0%, male: 84.0%), a routine check-up within 1 year (total: 76.8%, female: 79.1%, male: 71.9%) and daily cigarette use (total: 24.7%, female: 23.6%, male: 27.2%). Black participants more frequently reported being female (black: 69.1%, white: 66.8%), having an annual household income of less than US$25 000 (black: 59.6%, white: 49.7%), living in Flint during the FWC for the entire 18 months (black: 86.1%, white: 70.4%) and having a routine check-up in the last 12 months (black: 81.0%, white: 70.5%), whereas white participants more frequently reported their ethnicity as Hispanic or Latinx (4.3%) and smoking daily (31.2%) than black participants (Hispanic or Latinx: 0.8%, smoking daily: 21.2%).

Overall prevalence of health conditions

Crude estimates of the 11 health conditions showed that the FR adult population had a high burden of chronic conditions. More than one-third of participants reported having been told they have hypertension (45.6%), arthritis or other inflammatory conditions including fibromyalgia, lupus and gout (41.1%), depression (36.8%), and high cholesterol (34.7%) (table 2). When compared with the Michigan prevalence estimates from the 2019–2021 MiBRFSS, FR participants had higher age-adjusted prevalence of all conditions except ever being diagnosed with cancer, which FR participants had a lower age-adjusted prevalence (8.0% (7.5, 8.6)) compared with MiBRFSS participants (13.0% (12.5, 13.5)). FR participants had higher age-adjusted prevalence of common conditions, including arthritis and other pain conditions (42.3% (41.1, 43.5)) and hypertension (46.7% (45.4, 47.9)), than the Michigan population (arthritis and other pain conditions: 30.3% (29.6, 30.9) and hypertension: 35.2% (34.4, 36.1)), and also had a higher prevalence of diagnosis of conditions like kidney disease (8.1% (7.5, 8.6)) compared with MiBRFSS estimates (3.4% (3.1, 3.6)). Age-stratified prevalence of the conditions generally increased as age group increased (online supplemental table 2), except for asthma and current asthma diagnosis, which were stable through age 60 but decreased for participants age 60 and above, chronic bronchitis/COPD/emphysema, which increased across age groups to age 70 and then decreased for those 70 and older, and depression, which showed increasing prevalence across age groups until age 50, after which prevalence of diagnosis decreased sharply. For eight conditions, more than 40% of the individuals with the diagnoses were diagnosed after April 2014, including arthritis/fibromyalgia/gout/lupus, cancer, kidney disease, angina, high cholesterol, hypertension, heart attack and stroke (online supplemental table 3). Among those who had no diagnosis prior to April 2014, crude prevalence of conditions ranged from 2% (heart attack) to 25.7% (hypertension). Prevalence of arthritis (24.5%) and high cholesterol (20.4%) was also notable (online supplemental table 3).

Gender-stratified prevalence

Crude prevalence estimates of the chronic health conditions differed for female and male FR participants (table 2). Male participants reported higher prevalence of ever being told they have angina (8.3%), a heart attack (6.1%) or a stroke (4.5%) than female participants (angina: 6.2%, heart attack: 3.2% and stroke: 4.0%), and female participants had higher prevalence of all other conditions than male participants. Compared with MiBRFSS participants, age-adjusted estimates for female and male FR participants indicated both had higher prevalence of arthritis and other inflammatory conditions (FR female: 45.3% (43.8, 46.9); MiBRFSS female: 34.8% (33.8, 35.8); FR male: 36.9% (35.0, 38.8); MiBRFSS male: 25.5% (24.6, 26.5)), ever having asthma (FR female: 23.8% (22.8, 24.9); MiBRFSS female: 18.6% (17.8, 19.5); FR male: 17.2% (15.9, 18.6); MiBRFSS male: 13.3% (12.5, 14.2)), currently having asthma (FR female: 20.6% (19.7, 21.6); MiBRFSS female: 14.3% (13.5, 15.0); FR male: 13.8% (12.7, 15.1); MiBRFSS male: 8.0% (7.4, 8.8)), COPD/chronic bronchitis/emphysema (FR female: 16.1% (15.3, 17.0); MiBRFSS female: 9.0% (8.4, 9.6); FR male: 11.3% (10.3, 12.4); MiBRFSS male: 7.2% (6.7, 7.8)), depression (FR female: 37.7% (36.4, 39.0); MiBRFSS female: 26.7% (25.8, 27.7); FR male: 27.9% (26.3, 29.6); MiBRFSS male: 15.4% (14.5, 16.2)), kidney disease (FR female: 8.1% (7.5, 8.8); MiBRFSS female: 3.7% (3.3, 4.1); FR male: 8.1% (7.2, 9.1); MiBRFSS male: 3.0% (2.7, 3.4)), angina (FR female: 7.5% (6.8, 8.2); MiBRFSS female: 3.8% (3.4, 4.2); FR male: 8.4% (7.5, 9.5); MiBRFSS male: 5.4% (5.0, 5.9)) and hypertension (FR female: 47.9% (46.4, 49.5); MiBRFSS female: 32.6% (31.5, 33.7); FR male: 45.0% (43.0, 47.3); MiBRFSS male: 38.0% (36.7, 39.2)). Compared with female MiBRFSS participants, female FR participants also had higher prevalence of high cholesterol diagnoses (FR: 36.9% (35.6, 38.4); MiBRFSS: 33.3% (32.2, 34.5)). Male FR participants had higher prevalence of stroke diagnoses (5.6% (3.9, 5.4)) compared with male MiBRFSS participants (3.4% (3.0, 3.8)). Both female and male FR participants had lower prevalence of ever being diagnosed with any type of cancer than MiBRFSS participants (FR female: 8.3% (7.6, 9.1); MiBRFSS female: 14.6% (13.9, 15.3); FR male: 7.6% (6.7, 8.7); MiBRFSS male: 11.3% (10.7, 12.0)). The percentage of diagnoses made after April 2014 were similar for males and females, and the prevalence among those without diagnosis prior to April 2014 were similar to the patterns noted in the total population (online supplemental table 3).

Race-stratified prevalence

When stratified by race, white participants had higher crude prevalence of arthritis and other inflammatory conditions (43.9%), cancer (9.1%), COPD/chronic bronchitis/emphysema (16.4%), depression (45.3%),

Table 2 Crude and age-adjusted prevalence estimates of chronic conditions reported by adult Flint Registry participants and for the state of Michigan

Condition	N missing	Flint Registry Crude	Flint Registry Age-Adjusted MI	MiBRFSS estimates 2019–2021
Total (n=14 274)				
Arthritis/fibromyalgia/lupus/gout	167	41.1	42.3 (41.1, 43.5)	30.3 (29.6, 30.9)
Cancer (skin and any other type)	499	7.0	8.0 (7.5, 8.6)	13.0 (12.5, 13.5)
Asthma (ever)	525	22.3	21.8 (21.0, 22.6)	16.0 (15.4, 16.6)
Asthma (current)	657	19.0	18.5 (17.8, 19.3)	11.2 (10.7, 11.8)
Chronic bronchitis/COPD/emphysema	232	14.9	14.6 (13.9, 15.2)	8.1 (7.7, 8.6)
Depression	686	36.8	34.9 (33.9, 36.0)	21.2 (20.5, 21.9)
Kidney disease	449	7.5	8.1 (7.5, 8.6)	3.4 (3.1, 3.6)
Angina	887	6.8	7.7 (7.2, 8.3)	4.6 (4.3, 4.9)
High cholesterol	602	34.7	35.9 (34.8, 37.0)	34.5 (33.6, 35.3)
Hypertension*	422	45.6	46.7 (45.4, 47.9)	35.2 (34.4, 36.1)
Heart attack	409	4.1	4.4 (4.0, 4.8)	4.7 (4.4, 5.1)
Stroke	379	4.1	4.5 (4.1, 4.9)	3.6 (3.4, 3.9)
Female participants (n=9748)				
Arthritis/fibromyalgia/lupus/gout	87	42.6	45.3 (43.8, 46.9)	34.8 (33.8, 35.8)
Cancer (skin and any other type)	301	7.0	8.3 (7.6, 9.1)	14.6 (13.9, 15.3)
Asthma (ever)	319	24.5	23.8 (22.8, 24.9)	18.6 (17.8, 19.5)
Asthma (current)	419	21.3	20.6 (19.7, 21.6)	14.3 (13.5, 15.0)
Chronic bronchitis/COPD/emphysema	118	16.2	16.1 (15.3, 17.0)	9.0 (8.4, 9.6)
Depression	407	40.1	37.7 (36.4, 39.0)	26.7 (25.8, 27.7)
Kidney disease	256	7.3	8.1 (7.5, 8.8)	3.7 (3.3, 4.1)
Angina	563	6.2	7.5 (6.8, 8.2)	3.8 (3.4, 4.2)
High cholesterol	368	34.2	36.9 (35.6, 38.4)	33.3 (32.2, 34.5)
Hypertension*	249	45.7	47.9 (46.4, 49.5)	32.6 (31.5, 33.7)
Heart attack	240	3.2	3.5 (3.1, 4.0)	3.4 (3.0, 3.8)
Stroke	222	4.0	4.5 (4.1, 5.1)	3.9 (3.5, 4.3)
Male participants (n=4455)				
Arthritis/fibromyalgia/lupus/gout	69	38.3	36.9 (35.0, 38.8)	25.5 (24.6, 26.5)
Cancer (skin and any other type)	183	6.9	7.6 (6.7, 8.7)	11.3 (10.7, 12.0)
Asthma (ever)	192	17.4	17.2 (15.9, 18.6)	13.3 (12.5, 14.2)
Asthma (current)	224	14.0	13.8 (12.7, 15.1)	8.0 (7.4, 8.8)
Chronic bronchitis/COPD/emphysema	102	12.0	11.3 (10.3, 12.4)	7.2 (6.7, 7.8)
Depression	267	29.2	27.9 (26.3, 29.6)	15.4 (14.5, 16.2)
Kidney disease	181	7.9	8.1 (7.2, 9.1)	3.0 (2.7, 3.4)
Angina	300	8.3	8.4 (7.5, 9.5)	5.4 (5.0, 5.9)
High cholesterol	268	35.7	34.7 (32.8, 36.6)	35.7 (34.4, 37.0)
Hypertension*	161	46.2	45.0 (43.0, 47.3)	38.0 (36.7, 39.2)
Heart attack	155	6.1	6.0 (5.3, 6.9)	6.2 (5.7, 6.7)
Stroke	144	4.5	5.6 (3.9, 5.4)	3.4 (3.0, 3.8)

MiBRFSS estimates are weighted to reflect the Michigan population but are not age adjusted.
Includes total cohort estimates and estimates stratified by self-reported gender.
*Estimates from the MiBRFSS include data from 2019 and 2021 because the Cardiovascular Health Awareness module was not offered in 2020.
COPD, chronic obstructive pulmonary disease; MI, Michigan; MiBRFSS, Michigan Behavioral Risk Factor Surveillance System .

angina (7.4%), high cholesterol (38.9%) and heart attack (4.5%) compared with black participants (arthritis and other inflammatory conditions: 39.4%; cancer: 5.9%; COPD/chronic bronchitis/emphysema: 13.7%; depression: 30.8%; angina: 6.3%; high cholesterol: 32.7% and heart attack: 3.8%) (table 3). Compared with MiBRFSS participants, both black and white FR participants had higher prevalence of arthritis/gout/lupus/fibromyalgia (FR black: 36.9% (35.6, 38.2); MiBRFSS black: 29.5% (27.4, 31.7); FR white: 45.1% (42.9, 47.5); MiBRFSS

Table 3 Crude and age-adjusted prevalence estimates of chronic conditions reported by adult Flint Registry participants and for the state of Michigan, stratified by self-reported race

Condition	N missing	Flint Registry Crude	Flint Registry Age-Adjusted MI	MiBRFSS estimates 2019–2021
Black participants (n=8749)				
Arthritis/fibromyalgia/lupus/gout	353	39.4	36.9 (35.6, 38.2)	29.5 (27.4, 31.7)
Cancer (skin and any other type)	540	5.9	5.9 (5.4, 6.5)	6.7 (5.6, 7.9)
Asthma (ever)	541	21.3	21.2 (20.2, 22.3)	18.8 (17.0, 20.8)
Asthma (current)	605	18.6	18.5 (17.6, 19.5)	14.2 (12.6, 16.0)
Chronic bronchitis/COPD/emphysema	386	13.7	12.8 (12.0, 13.6)	7.8 (6.6, 9.1)
Depression	646	30.8	29.7 (28.6, 31.0)	17.4 (15.6, 19.3)
Kidney disease	500	7.6	7.4 (6.8, 8.1)	3.5 (2.8, 4.3)
Angina	740	6.3	6.1 (5.6, 6.7)	3.4 (2.7, 4.3)
High cholesterol	616	32.7	30.8 (29.6, 32.0)	33.3 (30.6, 36.1)
Hypertension*	466	48.9	46.2 (44.7, 47.7)	43.6 (40.8, 46.4)
Heart attack	497	3.8	3.5 (3.2, 4.0)	5.0 (4.0, 6.2)
Stroke	465	4.2	4.0 (3.6, 4.4)	5.0 (4.1, 6.1)
White participants (n=4493)				
Arthritis/fibromyalgia/lupus/gout	38	43.9	45.1 (42.9, 47.5)	31.5 (30.8, 32.3)
Cancer (skin and any other type)	137	9.1	10.7 (9.5, 12.0)	14.7 (14.2, 15.3)
Asthma (ever)	162	23.0	22.0 (20.5, 23.7)	15.7 (15.1, 16.4)
Asthma (crrent)	215	19.1	17.9 (16.6, 19.4)	10.9 (10.4, 11.5)
Chronic bronchitis/COPD/emphysema	65	16.4	16.3 (15.0, 17.7)	8.4 (7.9, 8.9)
Depression	196	45.3	42.6 (40.6, 44.7)	22.1 (21.4, 22.9)
Kidney disease	131	7.1	7.4 (6.5, 8.5)	3.4 (3.2, 3.7)
Angina	262	7.4	8.8 (7.8, 10.1)	4.9 (4.6, 5.3)
High cholesterol	177	38.9	40.1 (38.0, 42.4)	35.6 (34.6, 36.5)
Hypertension*	133	40.9	42.1 (39.9, 44.4)	34.9 (34.0, 35.8)
Heart attack	105	4.5	5.2 (4.4, 6.2)	4.8 (4.5, 5.1)
Stroke	112	3.6	4.5 (6.7, 5.5)	3.5 (3.2, 3.8)

Estimates from the MiBRFSS include data from 2019 and 2021 because the Cardiovascular Health Awareness module was not offered in 2020.
MiBRFSS estimates are weighted to reflect the Michigan population but are not age adjusted.
*Estimates from the MiBRFSS include data from 2019 and 2021 because the Cardiovascular Health Awareness module was not offered in 2020.
American Community Survey Population Estimates for age adjustment from table B01001, 2017–2021.
COPD, Chronic obstructive pulmonary disease; MI, Michigan; MiBRFSS, Michigan Behavioral Risk Factor Surveillance System.

white: 31.5% (30.8, 32.3)), asthma (ever (FR black: 21.2% (20.2, 22.3); MiBRFSS black: 18.8% (17.0, 20.8); FR white: 22.0% (20.5, 23.7); MiBRFSS white: 15.7% (15.1, 16.4)) and current (FR black: 18.5% (17.6, 19.5); MiBRFSS black: 14.2% (12.6, 16.0); FR white: 17.9% (16.6, 19.4); MiBRFSS white: 10.9% (10.4, 11.5))), COPD/chronic bronchitis/emphysema (FR black: 12.8% (12.0, 13.6); MiBRFSS black: 7.8% (6.6, 9.1); FR white: 16.3% (15.0, 17.7); MiBRFSS white: 8.4% (7.9, 8.9)), depression (FR black: 29.7% (28.6, 31.0); MiBRFSS black: 17.4% (15.6, 19.3); FR white: 42.6% (40.6, 44.7); MiBRFSS white: 22.1% (21.4, 22.9)), kidney disease (FR black: 7.4% (6.8, 8.1); MiBRFSS black: 3.5% (2.8, 4.3); FR white: 7.4% (6.5, 8.5); MiBRFSS white: 3.4% (3.2, 3.7)) and angina (FR black: 6.1% (5.6, 6.7); MiBRFSS black: 3.4% (2.7, 4.3); FR white: 8.8% (7.8, 10.1); MiBRFSS white: 4.9% (4.6,

5.3)). White participants also had a higher prevalence of ever being diagnosed with high cholesterol (40.1% (38.0, 42.4)) and hypertension (42.1% (39.9, 44.4)) compared with white MiBRFSS participants (high cholesterol: 35.6% (34.6, 36.5); hypertension: 34.9% (34.0, 35.8)). White FR participants had a lower prevalence of ever being diagnosed with cancer (10.7% (9.5, 12.0)) than MiBRFSS participants (14.7% (14.2, 15.3)), whereas the prevalence was similar for black FR participants (5.9% (5.4, 6.5)) and MiBRFSS (6.7% (5.6, 7.9)). More than 40% of diagnoses were made after April 2014 for most of the conditions for both black and white FR participants (online supplemental table 3). Notably, the prevalence of hypertension among those diagnosed after April 2014 only was higher for black participants (27.4%) compared with white (23.1%) (online supplemental table 3).

DISCUSSION

Our results indicate that FR participants have a higher prevalence of many lead-exposure-associated chronic conditions (9 of 11) compared with the MiBRFSS population estimates from the corresponding time period. If differences in the prevalence estimates for Flint and Michigan had arisen from differences in age and sex distributions for the two samples, age adjustment and stratification by sex would have substantially reduced or eliminated them; however, the differences persisted and even widened for some conditions when stratified by sex and adjusted for age. Michigan has persistent and long-standing disparities in chronic condition prevalence for black and white residents which stem from structural and institutional racism,[38 39] so we also stratified by race to understand if our high prevalence of chronic conditions was the result of having a higher percentage of black participants than Michigan's population. We found that FR participants still had a disparate prevalence of lead-associated chronic conditions when age-adjusted estimates were compared with their respective race estimates from the MiBRFSS. Overall, these analyses indicate that FR participants have a higher prevalence of lead-exposure-associated chronic conditions than the general Michigan population, even when considering age, sex and race.

To date, few studies have characterised the chronic health conditions of Flint adults before and after the water crisis. A study conducted 5 years after the FWC noted that 22.1% of respondents met Diagnostic and Statistical Manual-5 criteria for presumptive past-year depression but broader assessment of chronic health conditions was not undertaken.[17] The biannual Speak to Your Health! Flint community survey[40] produced community reports of survey responses including self-reported diagnoses of several health conditions weighted to reflect the Flint population. The 2017–2018 Speak to Your Health! Survey report[41] includes similar prevalence estimates of ever being diagnosed with asthma (23.2%), depression (37.3%), high blood pressure (43.3%), stroke (2.2%) and cancer (5.8%) for about 450 Flint residents. The Speak to Your Health! estimates also suggest there is a high prevalence of chronic disease. Importantly, the FR can assess prevalence while stratifying by key variables (sex and race) to characterise subsets of the Flint population that may need additional resources. The historical prevalence of these conditions among the exposed population is difficult to ascertain. The MiBRFSS annually produces reports of 3-year prevalence estimates of these and other chronic conditions for local health departments since 2005, including estimates for the Genesee County Health Department which serves Flint (see: https://www.michigan.gov/mdhhs/keep-mi-healthy/communicablediseases/epidemiology/chronicepi/bfrs/reglocal/michigan-brfs-regional-and-local-health-department-table); however, the Flint population accounted for only 24% of the Genesee County population in 2010 and by 2020 Flint's population had fallen to 20% of the total Genesee County population,[42] making it likely that the estimates do not represent the exposed population well. Additionally, population loss in the city of Flint from 2010 to 2020 (change: 20%)[42] renders serial cross-sectional surveillance data difficult to interpret even when it is available. The FR is designed to follow people over time and future survey waves of FR participants will allow us to track changes in prevalence of these 11 conditions and the 16 additional health conditions for which we did not have comparable MiBRFSS estimates (online supplemental table 4).

Likewise, historical estimates of lead exposure among Flint adults are difficult to ascertain. Evidence of lead exposure among children indicates higher prevalence of BLLs of 5 µg/dL or greater during the switch when compared with prevalence prior to April 2014 which varied according to estimated water lead level exposure,[43] and mean BLLs were elevated among children living in Flint compared with children outside the city even after an initial boil-water advisory was issued in September 2014[44]; however, blood lead testing in adults is typically done at the discretion of a healthcare provider and in the event of a known exposure.[45] The presence of lead in the Flint water supply was not public knowledge until late September 2015[1] and in the absence of population-wide testing for lead prior to April 2014, it is difficult to contextualise adult blood lead concentrations ascertained after the initial water switch to evaluate the effect of the FWC on adult BLLs. A study of reproductive-age females (12–50 years old) found a decrease in BLLs after 2015 but was unable to account for the change in the population receiving blood lead testing during this period (ie, high-risk screening vs population-wide testing), which was evidenced by the more than 3000% increase in number of people tested after the water switch.[46]

The ATSDR report on lead indicates that low-level lead exposure (BLLs of less than 10 µg/dL) has been associated with toxicity to every organ system because lead exerts impacts on mechanisms common across cell types.[11] The report notes that lead exposures have been extensively

associated with altered mood and behaviour, kidney disease, hypertension, heart disease and autoimmune and inflammatory dysregulation. Other health outcomes inconsistently associated with lead exposure include respiratory problems, including asthma and obstructive lung disease and cancer.[11] Our study found FR participants had higher age-adjusted prevalence of asthma, other chronic lung diseases, depression, kidney disease, angina, hypertension and stroke than the MiBRFSS participants. These patterns were generally consistent when we stratified our sample by gender but were less consistent when we stratified by race. Black FR participants had similar prevalence of elevated cholesterol and hypertension and lower prevalence of heart attack and stroke when compared with the black MiBRFSS respondents. White FR participants had higher prevalence of all the cardiovascular conditions except stroke, which was similar to the white MiBRFSS respondent prevalence. The prevalence of cancer for FR participants was lower than the prevalence for MiBRFSS participants. Recognising the time lag between exposure and the manifestation of disease, we expect that the continued surveillance of chronic conditions of Flint adults may identify changes in the prevalence of these chronic conditions and the present study can serve as an established baseline and will allow us to design studies that account for important coexposures, including use of cigarettes and primary healthcare access.

Exposure to traumatic events, both human-caused and natural, has been associated with changes in chronic conditions, including lung disease, arthritis, heart disease and hypertension. Studies of the Fukushima Power Plant disaster found higher prevalence of hyperlipidaemia and chronic kidney disease after the event compared with prior but found no evidence of higher frequency of hypertension,[47] and the parents of victims of the Volendam pub fire had higher incidence of hypertension compared with other parents in the city.[48] Acute myocardial infarction incidence was higher in a single hospital after Hurricane Katrina compared with prior,[49] and older adults who experienced stress during Hurricane Sandy, regardless of proximity to the storm, were found to have higher prevalence of arthritis and lung disease compared with those who did not experience stress.[50] Among participants in the Nurses' Health Study II, experiences of trauma were associated with a 30% elevated risk of cardiovascular disease compared with those who had not experienced trauma and had no symptoms of PTSD, and those with a combination of traumatic experiences and symptoms of PTSD had 70% higher risk of cardiovascular disease than those without.[51] World Trade Center rescue and recovery workers with symptoms of PTSD have higher odds of incident asthma than rescue and recovery workers without PTSD.[52] Importantly, a recent study of adults exposed to the FWC estimated about 24% of participants experienced PTSD symptoms in the past year.[17] Our study found higher prevalence of 11 conditions in an FWC-exposed population compared with Michigan prevalence estimates, except myocardial infarction. Because the FWC unfolded over 18 months and was both a lead-in-water exposure and a period of heightened stress with high risk of PTSD for the people exposed to it,[17 53] the FR's continued follow-up of chronic conditions will provide insight into the impact of a prolonged environmental disaster on the health of those exposed to it.

Measuring and contextualising chronic conditions is essential for community and healthcare organisations tasked with providing care and resources to those who were exposed to the FWC as they age.[54] Not only can this work help organisations identify the immediate needs of the Flint community, but it also serves as a source for data needed in grant applications, fund-raising efforts and policy decisions. In 2018, the Genesee County Board of Commissioners adopted a health-in-all-policies resolution[55] which requires knowledge of the health conditions experienced by people who were exposed to the FWC to enact. The FR conducts longitudinal data collection and establishing prevalence estimates supports local policy implementation and is important for identifying methods that can quantify the long-term effects of the FWC in adult populations, as was done in the World Trade Center Health Registry.[56] This work provides an example of a university–community collaboration designed to provide long-term public health surveillance to other communities affected by environmental crises.

LIMITATIONS

Our study has several limitations. The prevalence estimates of the 11 chronic conditions are derived from self-reported diagnoses. However, the questions we used were similar to the questions asked by the MiBRFSS, which minimises the potential for bias in the comparisons. We are limited by a lack of lead exposure assessment and do not know the extent to participants were directly affected by water lead levels. Though we assessed the degree to which the prevalence changed from before the start of the FWC to after, we cannot establish that individuals diagnosed after April 2014 were condition-free prior to April 2014 and we cannot assert causality of the FWC on the prevalence of the 11 conditions. Along with the water crisis, Flint has been subjected to several adverse circumstances, including manufacturing disinvestment, environmental contamination, structural racism and population decline, that may contribute to the prevalence of these conditions. Additionally, diagnosis of chronic conditions is impacted by an individual's access to healthcare, and prevalence is impacted by health behaviours like use of tobacco products. Programmes launched post-FWC to support community recovery, such as the Flint Medicaid Waiver, may have expanded access to healthcare, elevating the accessibility of diagnosis of these conditions in the FR population compared with the state of Michigan. Finally, the FR adult population includes both Flint residents and non-residents who were exposed to the

FWC through work or school attendance; thus, the FR is not representative of the Flint community. There are more females than males represented and more black participants than estimated by the ACS. Using age adjustment and stratification by sex and race helps to address this, but future studies may want to consider weighting to simulate population estimates.

CONCLUSIONS

Our results highlight the disparities in the prevalence of 11 chronic health conditions between adults exposed to the FWC and residents of Michigan and serve as an example of the capacity of a surveillance system that was implemented by a university at the request of the community impacted by the crisis. Because of the long latency period of these conditions, we anticipate that the prevalence of many of these conditions may increase, especially as exposed children become adults, thereby widening the disparities between Flint and Michigan and increasing the need for proactive surveillance, early detection and expanded healthcare services. Continued support of interventions designed to support FWC-exposed people, such as the Medicaid expansion and the FR, is critical to ensure the continued recovery of the Flint community. The City of Flint has committed to address policy-making through a lens of health equity,[57] and ongoing surveillance of people exposed to the FWC provides critical information about the health of the community to the leaders developing and enacting policies that prioritise and support the community's health.

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Competing interests MH is an author (What The Eyes Don't See, Penguin Random House) and speaker (Penguin Random House Speakers Bureau) and has provided testimony during congressional hearings as a child health expert. All other authors declare they have no conflicts of interest to report.

Patient and public involvement The Flint Community requested a public health registry to track long-term health of those exposed be created in response to the Flint water crisis and was instrumental in the design of the Flint Registry and the survey used in this manuscript. The Flint Registry has a Community and Partners Advisory Board which provides insight into community concerns and relevant surveillance questions. The public was not directly involved with the design of this study.

Patient consent for publication Not applicable.

Ethics approval Flint Registry participants gave informed consent for the collection and use of their data for public health surveillance and research. The Michigan State University Institutional Review Board approved secondary analyses of Flint Registry data under an expedited review (study number: STUDY00005777).

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