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# Firearm licensure, lead levels and suicides in Massachusetts

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ABSTRACT

Nationally, between 2011 and 2019, suicide was the second leading cause of injury death, and about half of all suicides were firearm related. An overlooked factor connecting firearms and suicide is lead exposure. Lead bullets and primers are used throughout the US and pose danger to adults and children. Most (not all) studies link lead to mental illness, while others link lead with suicide. Research has linked lead and firearm violence, but rarely examined the relationship among firearms, lead exposure, and suicide. We collected data for cities/towns in Massachusetts between 2011 and 2019 regarding the number of firearm licenses, suicides, prevalence of blood lead levels, and covariates. We hypothesized that; 1) towns with higher levels of licensure will have higher levels of firearm suicides but licensure will have little relationship with non-firearm suicide; 2) towns with higher levels of licensures would have higher rates of lead exposure; 3) higher lead levels would be associated with higher rates of suicide by all methods. Individuals living in towns with higher rates of licensure were significantly more likely to die in firearm suicides and all suicide types. They were not more or less likely to die from non-firearm suicides. Lead was a predictor of all suicide types. Our study appears to be the first to show the established firearm suicide relationships holds within municipalities in a single state. We provide evidence concerning the link between lead exposure and suicide, particularly from firearms, and provide a glimpse into the relationship between firearm prevalence and elevated blood lead levels.

## 1. Background

Suicide is the second leading cause of injury death in the United States, with almost 400,000 American causalities between 2011 and 2019.(Balestra, 2018; Ehlman, 2022; Ahmad and Anderson, 2021) During these years, over half of all suicides were firearm induced.(CDC, 2022) This is unsurprising, as the US has the highest rate of firearm ownership among high-income countries and highest subsequent rate of firearm suicides.(Grinshteyn and Hemenway, 2019) The firearm-suicide relationship has been investigated across cities, states, regions, and at the individual level.(Grinshteyn and Hemenway, 2019; Anglemyer et al., 2014; Miller et al., 2007) To our knowledge there has been no direct examination of this relationship within municipalities in an entire state. Among US states, Massachusetts has low levels of household firearm ownership, strong firearm laws and relatively low levels of firearm suicide.(Siegel et al., 2019; Kappelman and Fording, 2021) Massachusetts is one of the few states with firearm licensure laws.(Siegel et al., 2019; Kappelman and Fording, 2021) The state currently requires a single type of license for the purchase and possession of any firearm: A Class A License-To-Carry (which also allows for concealed carry). Importantly, the state monitors who has an active Class A license, so it can be determined which towns have the highest levels of firearm ownership.(Hoover et al., 2021) As of 2019, 14% of the adult state population had a firearm license.

An overlooked factor connecting firearms and suicide is lead exposure.(Cassleman et al., 2020; Domonoske, 2021; Skalny et al., 2021; Administration UD of VA Veterans Health, 2021; Reuben et al., 2019; Arnetz et al., 2020; Dickerson et al., 2020; Kim et al., 2015) Lead exposure is a significant health concern with well-documented deleterious health effects.(Braun et al., 2018; Power et al., 2014; Farooqui et al., 2017; Lanphear et al., 2018; Weisskopf et al., 2009) Lead bullets and primers are used throughout the United States with only California restricting some access, though no data are collected on the quantity or types of ammunition used.(Laidlaw et al., 2017; Dooley, 2019) When lead ammunition is discharged, dust is inhaled by persons in the vicinity which contributes to primary toxicity.(Hoover et al., 2021; Laidlaw et al., 2017) Secondary and tertiary exposures occur through particles adhering to the ground, skin and clothing that is later tracked

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throughout the community, causing contamination.(Hoover et al., 2021; Laidlaw et al., 2017) Tracking appears to be a major risk factor, possibly greater than immediate inhalation, given its propensity for repeated exposure.(Hoch and Bruce, 2019) For example, a US 1996 health hazard evaluation report identified the risks posed through tracking as dangerously high.(Health Hazard Evaluation Report: HETA-91-0346-2572, FBI Academy, Quantico, Virginia. U.S. Department of Health and Human Services, 1996) This finding was substantiated more than 10 years later in a publication by the Department of Defense (US).(Potential Health Risks to DOD Firing-Range Personnel from Recurrent Lead Exposure - NCBI Bookshelf, 2022) In these instances and in additional reviews, even with adjustments to ammunition type (e.g., less lead or jacketed), firearms pose a major lead risk.(Laidlaw et al., 2017; Rinsky et al., 2018) Additional vectors for lead exposure include age of housing stock (via paint particles or aging lead infrastructure), lead in water, certain occupations (hunting, construction work), and air pollution more globally.(Hoover et al., 2021; Lanphear et al., 2018)

Lead exposure has occasionally been linked to psychopathology. Some studies found that relatively low exposures can have strong associations with anxiety and depressive symptoms.(Eum et al., 2012; Li et al., 2017; Yu et al., 2017; Fan et al., 2020; Bouchard et al., 2009) For example, one study found that within low exposure levels, higher blood lead concentrations were associated with increased risk of depressive disorders.(Bouchard et al., 2009) Other studies found an association between lead and poverty but not between lead and mental health.(Ishitsuka et al., 2020; Jurczak et al., 2018) However, lead exposure remains linked to an increased prevalence of suicide, though suicide studies do not include both lead and firearms as risk factors.(Reuben et al., 2019; Arnetz et al., 2020; Dickerson et al., 2020; Kim et al., 2015) Limited research exists documenting the relationship among firearms, lead exposure, and suicide. We analyzed data from Massachusetts, which has good data on both current firearm licenses and probable bioavailable lead levels by town.(Hoover et al., 2021) We examined the cross-sectional relationships between firearms, pediatric blood lead levels as a proxy for bioavailable lead in a community, and suicide across the 351 Massachusetts towns.

From 2011 to 2019, Massachusetts had the lowest per capita rates among the 50 states of total firearm deaths (3.52/100,000; the overall US rate was 11.35) and firearm suicides (1.98/100,000; the overall US rate was 6.95).(CDC, 2022; Stats of the State - Suicide Mortality, 2022) The non-firearm suicide rate in Massachusetts was average (7.36/100,000; the overall US rate was 6.79).(CDC, 2022; Stats of the State - Suicide Mortality, 2022) From 2011 to 2019, Massachusetts' overall suicide rate was third lowest among the 50 states (8.4/100,000; overall US rate was 16.08) and the percentage that were firearm related were 21%, compared to the US rate of 51%.(CDC, 2022; Stats of the State - Suicide Mortality, 2022) We examined the years 2011–2019 due to data availability and combined all years together because of the low absolute numbers of firearm suicides (1209 across all 351 towns over nine years).

First, we hypothesized that—ceteris paribus—places with higher levels of firearm ownership would have higher levels of firearm suicide rates but firearm ownership levels have little relationship with non-firearm suicide (as has been found in larger ecological studies(Balestra, 2018; Grinshteyn and Hemenway, 2019; Anglemyer et al., 2014; Miller et al., 2007; Miller et al., 2002)). Next, we hypothesized that towns with higher levels of firearm ownership would have higher rates of lead exposure, due to leaded ammunition.(Laidlaw et al., 2017) Lastly, we hypothesized that higher blood lead levels would be associated with higher rates of suicide by all methods, possibly from the link between lead and mental illness.(Eum et al., 2012; Li et al., 2017; Yu et al., 2017; Fan et al., 2020; Ishitsuka et al., 2020; Kala and Jadhav, 1995; Jiang et al., 2015)

## 2. Methods

Our goal was to explain the cross-sectional variations in rates (per population) of firearm suicide, non-firearm suicide, and suicide by all methods, across Massachusetts towns.

### 2.1. Suicides

The MA Department of Public Health Registry of Vital Records and Statistics allowed us to use data on the number of suicides (total and via firearms) by town. For firearm specific suicides, ICD-10-CM codes were: X72 (Intentional self-harm by handgun discharge), X73 (Intentional self-harm by rifle, shotgun, and larger firearm discharge) and X74 (Intentional self-harm by other and unspecified firearm discharge). Death location was classified by where the shooting occurred (Fig. 1).

### 2.2. Firearm licensure

Data on the number of citizens with active Class A firearm licenses were obtained from the Massachusetts Department of Criminal Justice Information Services.(Hoover et al., 2021) Over the study period, Massachusetts had three types of licenses: Class A, Class B, and Federal Identification Cards. The overwhelming majority of licenses have been Class A. Indeed, the Class B license was discontinued after 2015, having been used for purchase and carry of small capacity firearms, and making up less than 1% of overall licensure in the State between 2011 and 2015. The Federal Identification Card is primarily for self-defense spray ("pepper spray"), and certain small capacity firearms for 15–18-year-olds only. Inclusion of Class B licenses and teenage Federal Identification Cards did not alter results and they were not included in the results shown. We divided the number of firearm licenses by the number of citizens aged 18+ for each of the 351 towns. We received data for the years of 2011–2019 (Fig. 2.A).

### 2.3. Lead exposure

There is no state-level monitoring system in place for lead exposure in adults. We use children's blood lead levels as a proxy. We used data on pediatric lead levels by town (Fig. 2.B).(Hoover et al., 2021; Lead Data and Reports, 2022) Children are at risk of lead exposure through adult vectors (e.g., inhalation), consumption (breast milk or certain foods), in addition to unique child vectors via hand-to-mouth behavior.(Braun et al., 2018; Lanphear, 2017) As such, while there is a great overlap, there are also salient differences between children and adult lead exposure pathways.

Children and adults are both at risk of exposure to lead in soil, which has been suggested to be the greatest single factor given its overlap with many other source (e.g., paint, dust, groundwater).(Mielke and Reagan, 1998; Li et al., 2018; Juhasz et al., 2011) Some studies suggest that children are more than five times as likely to consume soil than they are paint chips.(Mielke and Reagan, 1998; Li et al., 2018; Shellshear et al., 1975; Burgoon et al., 1995) Children are also at high risk of exposures from parental occupations and behavior, with evidence continuing to emerge.(Hoover et al., 2021; Rinsky et al., 2018; Gottesfeld and Pokhrel, 2011; Grashow et al., 2014) Children are more sensitive to lead, with smaller exposures showing up in higher blood concentrations.(Mielke and Reagan, 1998) While some studies suggest that adult blood lead levels are roughly 35% that of children, evidence supports the idea that child blood lead levels can reflect the extent to which lead is available in an environment.(Papanikolaou et al., 2005) We believe the prevalence of blood lead levels in children can provide a reasonable proxy for the extent to which bioavailable lead is present in said communities. Data came from the Massachusetts Bureau of Environmental Health, which tests the capillary blood lead levels of a representative sample of children annually, from 9 to 47 months.(Lead Data and Reports, 2022) There was a total of 14 small towns that did not have enough children to consistently report and were excluded from analysis.

We believe that firearm use is a contributor to elevated blood lead levels and it has been used as a proxy for firearm related lead exposure in

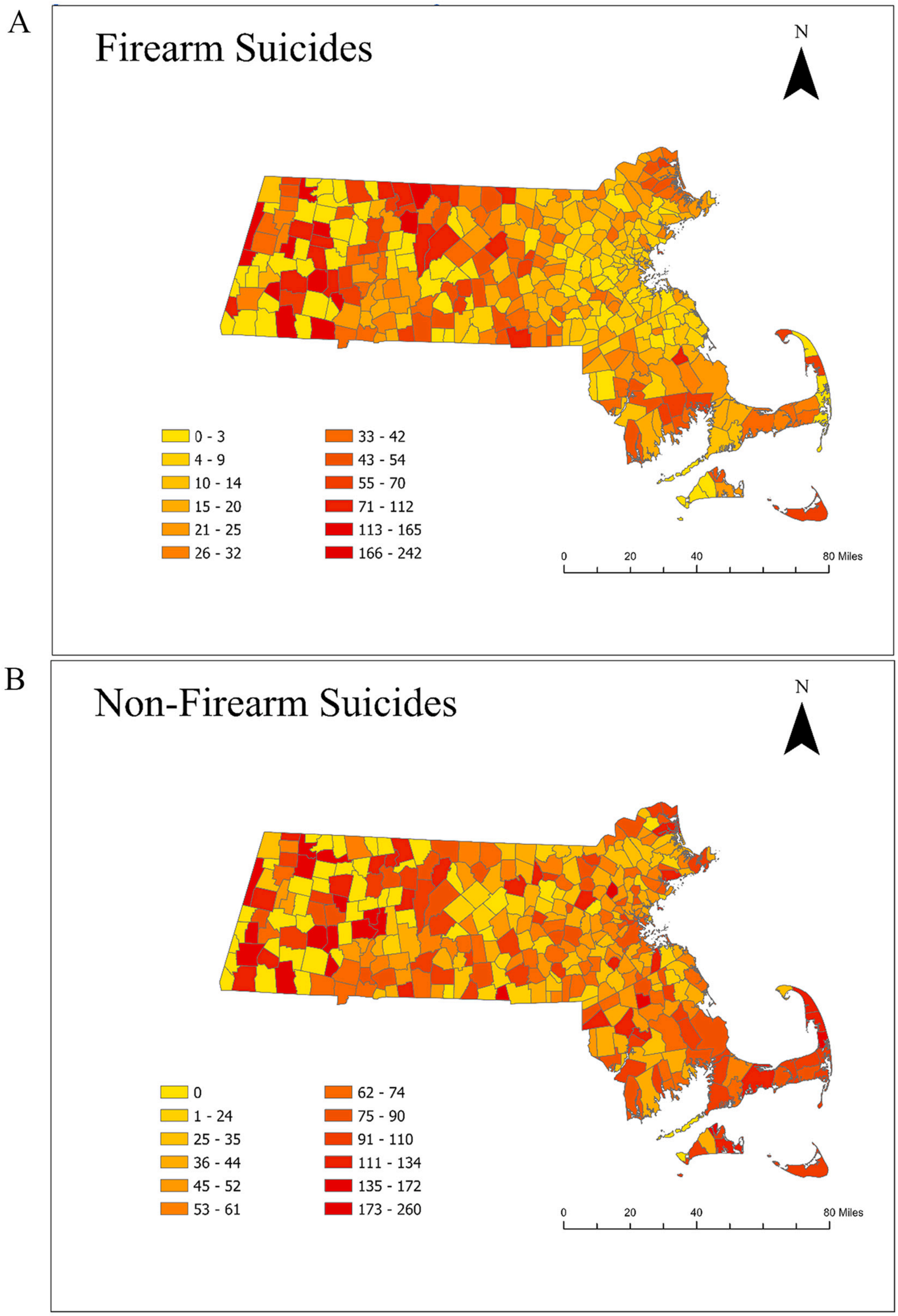


**Fig. 1.** Firearm and all-cause suicides per 100,000, 2011–2019.

other studies.(Hoover et al., 2021) To examine the potential overlap between firearms as a vector of both suicide and lead exposure, we initially included other sources of lead (such as prevalence of aging housing, lead in water, and occupational risks from construction and agriculture) and presence of firing ranges in a community.(Hoover et al., 2021) *t*-tests between lead levels in cities/towns with ranges compared to those that did not were not significant ($t(334) = 1.74$, $p = .08$). Variables for other sources of lead exposure were not significant predictors in the regression models and did not alter overall regression results; results are reported without them.

### *2.4. Covariates*

Covariates include town rates of poverty, unemployment, and armed

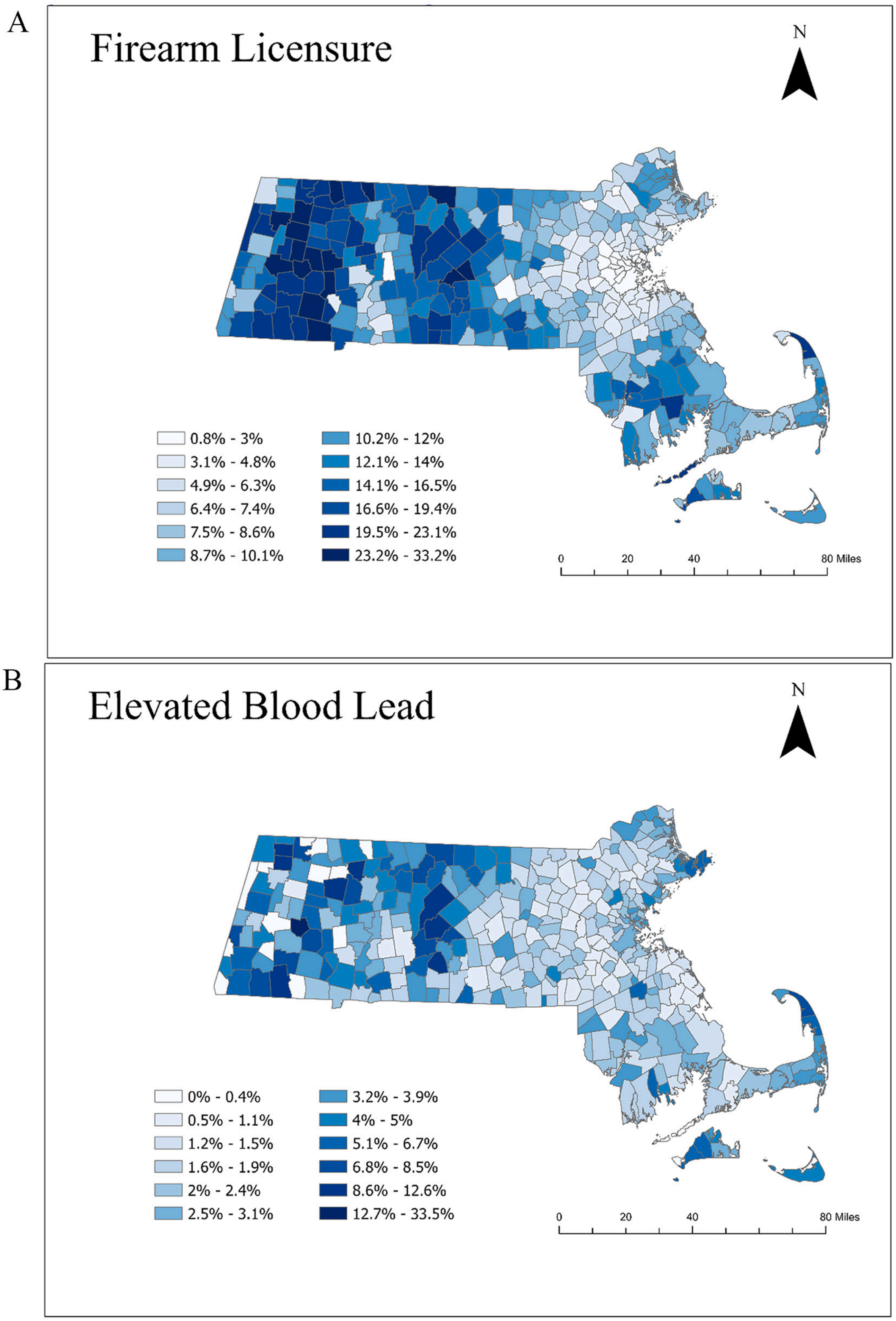


**Fig. 2.** Class A firearm licensure and pediatric blood lead levels, 2011–2019.

forces status . Data came from the American Community Survey 5-year U.S. Census estimates.(*Census Data Report*, 2022) Between 2011 and 2019, Massachusetts was relatively affluent (92% of households above the poverty line) and had low unemployment (5%). Less than 1 % of the population were active-duty service members. For measures of poverty, unemployment, and armed forces, 3 small towns were missing from the census data. These towns were excluded in the multivariate analyses.

### 2.5. Data analysis

We began by measuring covariates and outcome variables. We then ran a correlational matrix between covariates and outcome variables to identify significant relationships. For our cross-sectional analyses, we ran a stepwise regression for three outcomes (firearm suicide rates, non-firearm suicide rates, and total suicide rates). This method allows us to model changes in continuous variables as a function of other variables.(Gelman et al., 2020) The stepwise approach was adopted in order to examine a change in the dependent variable as function of the independent variables included.(Gelman et al., 2020) We first examined the relationship of elevated blood levels and each outcome variable, then added firearm licensure, and finally poverty, unemployment, and armed forces. To help show the size of differences related to firearm licensure, we also used a prevalence analysis by dividing the towns into quartiles by rates of firearm licensure. Each quartile contained 88 counties, except for quartile 2 (87). The towns in the lowest quartile of firearm licensure rates were the baseline, and the other quartiles were compared to that base in terms of the firearm suicide rate, the non-firearm suicide rate, the total suicide rate, prevalence of elevated blood lead level, poverty, and unemployment rates. We used a similar analysis to show the size of the differences related to lead by dividing the towns into quartiles by rates of blood lead levels. Correlational analysis was conducted using R statistical software.(*RStudio: Integrated Development for R. RStudio*, 2022) All other data analysis was conducted through Stata.(*Stata Statistical Software: Release 17*, 2022)

### 2.6. Ethical statement

The IRB at Harvard T.H. Chan School of Public Health reviewed the study and declared it to be non-human subjects research; as such the study did not undergo full review with the IRB. Data collected as part of the study were all publicly available, upon request, and were provided with no personal identifying information. IRB approval was obtained in June of 2022.

## 3. Results

### 3.1. Descriptive statistics

Between 2011 and 2019, there was a gradual net decline in prevalence of elevated child BLL in Massachusetts from 4.33% in 2011 to 1.6% in 2019 (Table *1*).(Bureau, 2020) This is in contrast with the number of active firearm licenses, which increased from 235,999 (or 8.7% of the population) to 402,135 (13.3%). Suicides increased during the study period; firearm suicides rose from 113 to 136 and non-firearm suicides from 478 to 505.

### 3.2. Bivariate correlational results

Cross-sectional bivariate results show that elevated blood lead levels were significantly correlated with both firearm suicide, non-firearm suicide, total suicide rates and firearm licensure (Fig. 3). Elevated lead levels were also significantly positively correlated with poverty and unemployment. Firearm licensure rates were significantly correlated with firearm suicide and total suicide rates but were not correlated with non-firearm suicide rates or unemployment and were negatively correlated with poverty.

**Table 1**
Descriptive statistics.

| Variable | N | Min | Max | Median | Mean | Standard deviation |
|---|---|---|---|---|---|---|
| Elevated blood prevalence (%) | 336 | 0.42% | 12.57% | 2.13% | 2.85% | 2.02% |
| Firearm licensure (%) | 351 | 0.81% | 33.18% | 9.60% | 11.07% | 6.39% |
| Firearm suicides per 100,000 | 351 | 6.65 | 242.13 | 17.97 | 28.11 | 34.82 |
| Non-firearm suicides per 100,000 | 351 | 0.00 | 260.27 | 0.05 | 60.52 | 43.63 |
| Poverty rate (%) | 348 | 0.72% | 29.61% | 5.74% | 7.10% | 4.51% |
| Unemployment rate (%) | 348 | 0.00% | 8.03% | 4.16% | 4.22% | 1.23% |
| % working in armed forces | 348 | 0.00% | 7.79% | 0.03% | 0.10% | 0.44% |

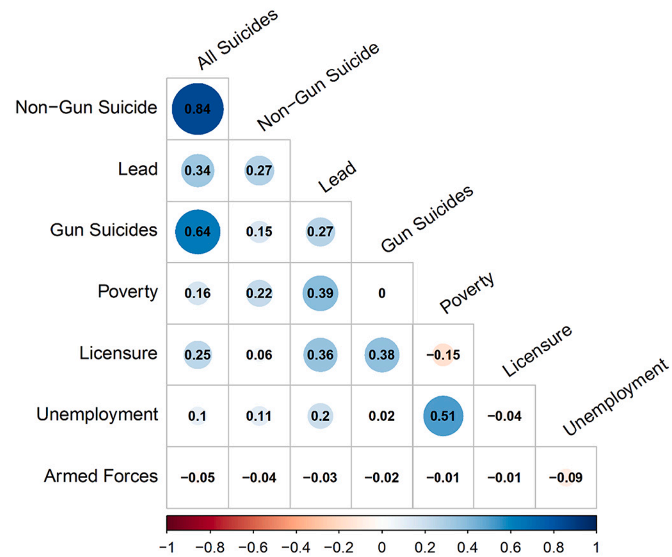


**Fig. 3.** Pearson Correlation Coefficient Matrix.
Red circles indicate negative significant correlation at 0.05 level; Blue circles indicate positive significant correlation at 0.05 level.

### 3.3. Multivariate regression results

Perhaps our most novel result is that on its own, elevated blood lead levels were a predictor of firearm suicide, non-firearm suicide and total suicide. The inclusion of firearm licensure as well as all other independent variables did not alter this relationship, including when all independent variables were added to the regression (Table 2). Firearm licensure was a significant predictor of the firearm suicide rate and the total suicide rate in all the models. It was never a significant predictor of non-firearm suicide. The beta coefficients for the full multivariate analyses indicate that a one standard deviation change in firearm licensure is associated with a change of 11.9 firearm and 11.5 all-suicides. The beta coefficients for the full non-firearm and all-suicides regressions indicate that one standard deviation change in blood lead levels are associated with a change of 4.9 non-firearm suicides and 13.5 all-suicides. In the full models for firearm suicide, non-firearm suicide and total suicide, the adjusted R2 were 0.15, 0.08 and 0.13, respectively.

### 3.4. Prevalence rate analysis

Individuals living in towns in the highest quartile of firearm ownership were 3.6 times more likely to die of firearm suicide than those in towns in the lowest quartile (Table 3). They were no more or less likely to die from non-firearm suicides. They were 1.7 times more likely to die from suicides in all methods combined. Individuals living in towns in the highest quartile of firearm ownership were also 1.7 times more likely to have elevated lead levels and 23% less likely to live in poverty. Individuals living in towns in the highest quartile of elevated lead levels were 2.5 times more likely to die from firearm suicides, 1.7 times more likely to die from non-firearm suicides and 1.9 times more likely to die from all suicide methods combined (Table 3). They were also 1.6 times more likely to have a firearm license, 2.3 times more likely to live in poverty and 1.2 times more likely to live in areas with high rates of unemployment.

**Table 2**
Stepwise multivariable regression analysis of predictors of firearm suicides, non-firearm suicides, and all suicides.

| | Univariable | | Model 1 | Model 2 |
|---|---|---|---|---|
| | β (95% CI) | Adjusted $R^2$ | $N = 336$ | $N = 334$ |
| Predictors of firearm suicide | | | β (95% CI) | β (95% CI) |
| Lead prevalence | 429.65 (262.70, 596.60)** | 0.07 | 241.41 (71.09, 411.74)** | 246.70 (49.94, 443.47)* |
| Firearm licensure | 182.63 (128.57, 236.68)** | 0.11 | 172.39 (115.99, 228.79)** | 171.055 (110.31, 231.79)** |
| Poverty rate | 2.25 (−79.62, 84.13)* | 0 | | −8.03 (−101.77, 85.72) |
| Unemployment rate | 76.19 (−223.32, 375.70) | 0 | | −23.97 (−295.28, 343.22) |
| Armed forces rate | −144.16 (−980.33, 692.02) | 0 | | −80.06 (−804.10, 643.98) |
| Model 1 adjusted $R^2$ | 0.16 | | | |
| Model 2 adjusted $R^2$ | 0.15 | | | |
| Predictors of non-firearm suicide | | | | |
| Lead prevalence | 573.30 (355.34, 791.25)** | 0.07 | 607.58 (373.67, 841.48)** | 457.42 (189.63, 725.22)** |
| Firearm licensure | −9.38 (−81.25, 62.49) | 0 | −31.39 (−108.85, 46.06) | −1.12 (−83.79, 81.54) |
| Poverty rate | 189.22 (88.91, 289.52) | 0.04 | | 125.85 (−1.73, 253.43) |
| Unemployment rate | 440.87 (69.49, 812.26)* | 0.01 | | −3.53 (−438.02, 430.95) |
| Armed forces rate | −291.06 (−1335.39, 753.28) | 0 | | −323.01 (−1308.42, 662.40) |
| Model 1 adjusted $R^2$ | 0.07 | | | |
| Model 2 adjusted $R^2$ | 0.08 | | | |
| Predictors of all suicides | | | | |
| Lead prevalence | 969.58 (681.69, 1257.47)** | 0.11 | 822.26 (516.15, 1128.38)** | 673.65 (321.86, 1025.44)** |
| Firearm licensure | 165.72 (68.02, 263.43)** | 0.03 | 134.91 (33.55, 236.28)** | 164.55 (55.96, 273.15)** |
| Poverty rate | 190.39 (50.62, 330.16)** | 0.02 | | 119.73 (−47.87, 287.34) |
| Unemployment rate | 519.58 (5.72, 1033.43)* | 0.01 | | 28.83 (−541.94, 599.59) |
| Armed forces rate | −473.19 (−1914.82, 968.45) | 0 | | −442.79 (−1737.27, 851.70) |
| Model 1 adjusted $R^2$ | 0.13 | | | |
| Model 2 adjusted $R^2$ | 0.13 | | | |

* significant at the 0.05 level.
** significant at the 0.01 level

**Table 3**
Prevalence ratios by quartiles of firearm licensure and elevated pediatric blood lead levels.

| Elevated BLL prevalence | Quartile 1 reference | Quartile 2 PR (95% CI) | Quartile 3 PR (95% CI) | Quartile 4 PR (95% CI) |
|---|---|---|---|---|
| Firearm licensure | 8.49% | 1.14 (0.54, 1.75) | 1.30 (0.50, 2.10)** | 1.60 (0.74, 2.45)** |
| Poverty | 4.25% | 1.35 (0.60, 2.10)** | 2.00 (0.62, 3.38)** | 2.32 (0.82, 3.81)** |
| Unemployment | 3.81% | 1.10 (0.84, 1.35)** | 1.16 (0.82, 1.49)** | 1.20 (0.84, 1.57)** |
| Firearm suicides per 100,000 | 18.25 | 1.22 (0.00, 2.46) | 1.48 (0.00, 3.09)* | 2.45 (0.00, 5.43)** |
| Non-firearm suicides per 100,000 | 45.18 | 1.30 (0.54, 2.06)** | 1.54 (0.56, 2.53)** | 1.71 (0.44, 2.99)** |
| All suicides per 100,000 | 63.43 | 1.28 (0.63, 1.92)** | 1.53 (0.70, 2.35)** | 1.89 (0.49, 3.28)** |
| Firearm licensure | | | | |
| Elevated pediatric BLLs | 2.30% | 1.08 (0.36, 1.80) | 1.26 (0.37, 2.14)* | 1.65 (0.52, 2.78)** |
| Poverty | 8.68% | 0.78*(0.7, 0.86) | 0.72*(0.66, 0.78) | 0.77**(0.71, 0.83) |
| Unemployment | 4.33% | 0.97 (0.93, 1.01) | 0.92 (0.88, 0.96) | 0.96 (0.92, 1) |
| Firearm suicides per 100,000 | 14.19 | 1.52*(1.34, 1.7) | 1.84**(1.59, 2.09) | 3.56**(2.95, 4.17) |
| Non-firearm suicides per 100,000 | 76.75 | 1 (0.81, 1.19) | 0.97 (0.81, 1.13) | 0.95 (0.78, 1.12) |
| All suicides per 100,000 | 70.29 | 1.12 (0.5, 1.81) | 1.23*(0.55, 1.89) | 1.66**(0.44, 2.89) |

* Significant at the .05 level.
** Significant at the .01 level

## 4. Discussion

We found that among the 351 towns in Massachusetts (2011–2019), individuals living in towns with higher rates of firearm levels/licenses were significantly more likely to die in firearm suicides and in all-suicides. They were not more or less likely to die from non-firearm suicide, which is consistent with the well-established relationship between firearms and overall suicide rates – that firearm availability not only increases firearm suicide but the overall likelihood of someone dying of suicide from any method. Our results for towns within a single state is consistent with other ecological research across cities, states, and regions in the United States.(Grinshteyn and Hemenway, 2019; Anglemyer et al., 2014; Miller et al., 2007) It is also inconsistent with the claim that access to lethal means has no effect on the likelihood of dying by suicide.(Grinshteyn and Hemenway, 2019; Anglemyer et al., 2014; Miller et al., 2007)

We appear to be the first to include lead prevalence in the analysis of the relationship between firearms and suicide. We find that both firearms ownership levels and pediatric blood lead levels, as a proxy for lead in a community, are significantly associated with suicide. This is the second study across Massachusetts towns showing a strong relationship between firearm licensure and child blood lead levels. The first study examined only one year (2017) and the current article expands the time period to 9 years.(Hoover et al., 2021) The current article suggests that firearms may increase deaths by suicide directly by increasing the case fatality rate (firearms are the most lethal method for suicide in the United States) and firearm use may increase suicide indirectly via lead exposure.(Stats of the State - Suicide Mortality, 2022) It may be that firearm availability results in substitution in the methods of suicide attempts (more firearm attempts, fewer non-firearm attempts), but any net effect on lowering non-firearm suicide death rates is masked by the markedly lower case-fatality rate of non-firearm suicide and the effect of firearm use on blood lead levels – which may increase suicide attempts.

We establish a link between lead and suicide, which corroborated evidence provided in some other studies.(Dickerson et al., 2020) For example, population-level studies published in 2015 and 2022 linked airborne and occupational lead pollution with increased risks for suicide.(Kim et al., 2015; Andersen et al., 2022) The 2015 article in particular found compelling evidence towards the strong association between elevated blood lead levels and suicide.(Kim et al., 2015) In one study of lithium in water and psychopathology, authors found evidence suggesting lead exposure contributes to suicidality.(Brown et al., 2018) While we substantiated this link between lead and suicide, the relationship of lead with mental illness is not fully understood. Some studies suggest low-level lead exposures have strong associations with anxious and depressive symptoms.(Eum et al., 2012; Li et al., 2017; Yu et al., 2017; Fan et al., 2020) Other studies find associations to certain outcomes (e.g., increased rates of hostility) but not to psychiatric conditions.(Ishitsuka et al., 2020; Jurczak et al., 2018) In one study, lead exposure attenuated the relationship between war trauma and mental health(Arnetz et al., 2020); in several others, lead appeared to contribute to hypothalamic-pituitary-adrenal axis dysfunction.(Ishitsuka et al., 2020; Rossi-George et al., 2011; Virgolini et al., 2005) Other research suggests lead interrupts neurotransmitter activity related to stress (serotonin, dopamine, adrenaline), contributing to depression and anxiety.(Ishitsuka et al., 2020; Kala and Jadhav, 1995; Jiang et al., 2015) While limited to case studies, symptoms of psychiatric illness in Veteran populations appear to mimic those of extreme lead toxicity (e.g., elevated anxiety symptoms).(Cassleman et al., 2020) In summary, there appears to be a link between lead and mental illness, but much is still unknown.

### 4.1. Limitations

One limitation of our study is that the data come from only one state—Massachusetts. Massachusetts is a middle-sized state in terms of population and is divided into 351 mostly small towns. Compared to other states, it has few firearms and thus low rates of firearm suicide and overall suicide. Thus, even when looking at a 9-year period, many towns had low absolute numbers of firearm suicides (the mean number of firearm suicides per town was 3.4). Thus much of the variation in firearm suicide rates across towns could be due to stochastic variation. This is likely one of the reasons that our predictive models were low even in multivariate analyses. The low rate of firearm suicide in Massachusetts also means that even a large change in firearm suicide will not lead to a large change in overall suicide rates. While the percentage of suicide with firearms was over 50% for the US as a whole, it was 21% for Massachusetts.(Miller et al., 2007) That makes it difficult to detect an effect of firearm prevalence on overall suicide rates.

Perhaps the major limitation of our study is that we used a proxy measure for lead – pediatric blood lead levels – which does not itself denote adult exposure. While adults and children can have similar vectors of exposure, the scope and magnitude are different.(Hoover et al., 2021; Braun et al., 2018; Landrigan and Todd, 1994; Levin et al., 2008; O'Flaherty, 1998) For example, it is possible that children exhibited high blood lead levels due to child activities, such as hand-to-mouth behavior and eating leaded paint. However, in the case of hand-to-mouth behavior, adults may also be at risk of exposure from lead in soil.(Mielke and Reagan, 1998; Li et al., 2018; Juhasz et al., 2011; Shellshear et al., 1975; Burgoon et al., 1995; Almansour et al., 2019) Fortunately, Massachusetts has strong regulations concerning child lead exposure sources and appears to have had success in lowering these exposures in children.(2020 Annual Childhood Lead Poisoning Surveillance Report, 2022) In addition, some studies suggest children are far more likely to consume lead from soil than from paint.(Mielke and Reagan, 1998; Shellshear et al., 1975) When we included lead paint, lead in water, and occupational exposures (construction, agriculture) as variables in the analyses, the main results did not change.

Another proxy in our study is firearm licensure, as it does not represent firearm ownership or firearms use. It only indicates that the license holder has a license to own and carry a firearm.(Hoover et al., 2021; *Renew a Firearms License | Mass.gov*, 2022) We have no measure of how often firearms are fired or where the firearm use occurred, and our measure does not account for illegally held firearms. We have no data on ammunition type, although lead remains the most popular in many firearm circles and, even in ammunition with a lighter load of lead, there is still great risk of lead exposure from tracking.(Laidlaw et al., 2017; Rinsky et al., 2018; Tripathi et al., 1991) More broadly, our study lacked data on many other potential causes of suicide, such as mental health status, clinical depression, suicide ideation and suicide attempts. Our regressions thus undoubtedly suffer from some omitted variable bias. Finally, our study is cross-sectional. We cannot ascribe causation among the correlated variables.

However, it is noteworthy that our findings are consistent with other studies and with our a priori hypotheses. Towns with more firearm owners per capita have more firearm suicides per capita. There is no relationship between levels of firearm licensure and rates of non-firearm suicide. Towns with higher rates of elevated blood lead levels have higher rates of firearm suicide, non-firearm suicide and overall suicide. For explaining variations in firearm suicide, firearm levels are a stronger explanatory variable than blood lead levels.

## 5. Conclusion

Firearm use can increase lead exposure, and higher lead levels may reduce mental health and increase suicide attempts. Our study is the first to include both firearms and blood lead levels in an examination of suicide. Our findings suggest that to explain variations in firearm suicide, variations in firearm levels are the key, with lead exposure playing a secondary role. However, we have previously provided evidence that lead on its own may be related to suicidality, unrelated to firearm-related lead exposure.(Hoover et al., 2021) Many US ecological studies have shown that firearm prevalence is significantly related to firearm suicides, but not to non-firearm suicides.(Miller et al., 2007) While these other studies have examined variations across cities, states, and regions, ours appears to be the first to show that these firearm suicide relationships also hold within political areas in a single state. More research is clearly needed. Future studies could directly examine blood lead levels and mental health sequalae in a firearm-owning community or firearm ownership and blood lead levels in a psychological outpatient setting. Conducting a similar study to ours that examined these relationships within a single city and using direct soil samples to determine soil lead levels could provide another way to examine these relationships.

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## CRediT authorship contribution statement

**Christian Hoover:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Aaron J. Specht:** Methodology, Validation, Writing – review & editing. **David Hemenway:** Methodology, Validation, Formal analysis, Writing – review & editing, Supervision.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will only be made available upon request and with approval by authorship team.

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