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Local Residential Segregation Matters: Stronger Association of Census Tract Compared to Conventional City-Level Measures with Fatal and Non-Fatal Assaults (Total and Firearm Related), Using the Index of Concentration at the Extremes (ICE) for Racial, Economic, and Racialized Economic Segregation, Massachusetts (US), 1995–2010

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Abstract Research on residential segregation and health, primarily conducted in the USA, has chiefly employed city or regional measures of racial segregation. To test our hypothesis that stronger associations would be observed using local measures, especially for racialized economic segregation, we analyzed risk of fatal and non-fatal assault in Massachusetts (1995–2010), since this outcome is strongly associated with residential segregation. The segregation metrics comprised the Index of Concentration at the Extremes (ICE), the Index of Dissimilarity, and poverty rate, with measures computed at both the census tract and city/town level. Key results were that larger associations between fatal and non-fatal assaults and residential segregation occurred for models using the census tract vs. city/town measures, with the greatest associations observed for racialized economic segregation. For fatal assaults, comparing the bottom vs. top quintiles, the incidence rate ratio (and 95% confidence interval (CI)) in models using the census tract measures equaled 3.96 (95% CI 3.10, 5.06) for the ICE for racialized economic segregation, 3.26 (95% CI 2.58, 4.14) for the ICE for income, 3.14 (95% CI 2.47, 3.99) for poverty, 2.90 (95% CI 2.21, 3.81) for the ICE for race/ethnicity, and only 0.93 (95% CI 0.79, 1.11) for the Index of Dissimilarity; in models that included both census tract and city/town ICE measures, this risk ratio for the ICE for racialized economic segregation was higher at the census tract (3.29; 95% CI 2.43, 4.46) vs. city/town level (1.61; 95% CI 1.12, 2.32). These results suggest that, at least in the case of fatal and non-fatal assaults, research on residential segregation should employ local measures, including of racialized economic segregation, to avoid underestimating the adverse impact of segregation on health.

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Background

At a time of mounting economic polarization within and across myriad cities and countries [1–3], along with political tensions involving ethnic and anti-immigrant discrimination [4–6], it is important to ask if the predominant approach to studying the health impacts of residential segregation is sufficient. Typically, in both population health and social science research, measures of residential segregation are computed at the city or regional level, and these measures usually pertain to racial segregation [7–11] or, less commonly, economic segregation [12, 13]. Indicative of the conventional approach, a 2009 review article on segregation and health focused solely on racial segregation and stated that: "most social scientists utilize measures that acknowledge 2 scales of geography: subareas (e.g., neighborhoods) situated within larger overall geographic areas (e.g., cities or metropolitan areas) [8, p.180]." Such measures provide solely city or metropolitan area measures of segregation, which are the norm for measures reported by the US census [7].

Our concern, building on recent work on extreme concentrations of privilege and deprivation [14–21] and on local segregation [22–25], is that health outcomes are more likely to exhibit stronger associations with segregation measures that (1) are computed at the local, compared to city level, and (2) are computed jointly in relation to income and race/ethnicity, rather than only one or the other. To test our hypothesis, we selected an outcome well-documented to be positively associated with adverse racial residential segregation and economic deprivation: fatal and non-fatal assaults, especially those involving firearms [26–30]. The conceptual underpinning for our hypothesis is provided by the ecosocial theory of distribution, which addresses how people's societal, historical, and ecological context shapes not only population health but also how it is analyzed [6, 31].

Methods

Study Population

Our observational study employed statewide data for Massachusetts for 1995–2010 from Massachusetts Department of Public Health (MDPH) vital statistics [32, 33] and the Weapons-Related Injury Surveillance System (WRISS) [30, 34]. Rendering Massachusetts a suitable site, the state has stark racial/ethnic inequities in risk of homicide [33] and non-fatal weapons-related assaults [30], and also high levels of urban income inequality [35, 36], and racial segregation [37]. The study was approved by the Institutional Review Boards of the Harvard T.H. Chan School of Public Health (Protocol IRG15-0693) and the Massachusetts Department of Public Health (Project 724047–1).

Each case's record included data on the case's age and residential address at the time of the assault, gender, race/ethnicity (using the US census categories, provided below), and also whether the assault was due to firearm or some other cause [32, 38]. For these analyses, we conceptualized race/ethnicity as a social construct arising from inequitable race relations that historically have been linked to, but are not identical to, inequitable social class relations [5, 6].

We employed ArcGIS [39] to geocode the residential address of each case to its latitude and longitude; only 18 (0.7%) of the 2589 fatal cases and 1492 (5.2%) of the non-fatal cases could not be geocoded to this level of precision. To account for changes in census tract boundaries, we used the Geolytics Neighborhood Change Database [40]. To compute rates at the census tract and city/town levels, we used US Census decennial population denominator data for 1990 and 2000, and American Community Survey data for 2008–2012 (with the 5-year average centered around 2010), and interpolated counts for intercensal years [40–42]. To create a data structure in which all city/towns contained at least 1 census tract, we aggregated 59 small towns (out of the state's 351 city/towns) which were nested within census tracts that contained ≥2 towns into 21 "super towns" containing 1 census tract each; the population in these small towns accounted for 1.1% of the person-time under the period of study (1995–2010).

Area-Based Measures: Index of Concentrations at the Extremes, Index of Dissimilarity, and Poverty Rate

We used the US Census data [40–42], to generate our three types of area-based measures at the census tract and city/town levels: the Index of Concentrations at the Extremes (ICE) [14, 19–21], the Index of Dissimilarity [7], and the poverty measure [43, 44]. In Table 1, we provide the formulas and conceptual and operational definitions of the variables employed.

Briefly stated, the ICE was developed in 2001 by Douglas Massey [14], a leading US scholar on racial segregation and economic stratification [48–50]. He designed the ICE to quantify the extent to which an area's residents are concentrated into groups at the extremes of socioeconomic deprivation and privilege. A value of −1 means that 100% of the population is concentrated in the most deprived group and a value of 1 means that 100% of the population is concentrated into the most privileged group. Primarily employed in social science research [14, 55–57], the ICE has begun to be used in public health research [15–21, 45, 58–60], including our novel extension to compute ICE measures for both racial segregation and racialized economic segregation [19–21]. The Index of Dissimilarity, one of the most widely used measures of racial segregation [7–11], in turn measures the extent to which a region's population (e.g., in a city) would need to be redistributed across sub-units (e.g., census tracts) to achieve a uniform distribution. Measures of area-based poverty rate are widely used in public health research and reports [44, 47].

Statistical Analyses

We first assessed characteristics of the total MA population and the cases in relation to individual, census tract, and city/town characteristics. We next computed the average age-standardized annual incidence of the fatal and non-fatal weapons-related assaults stratified by these same individual, city/town, and census tract characteristics.

Drawing on standard multilevel approaches for modeling small-area disease rates [61, 62], we used a Poisson multilevel model framework to model relationships between, respectively, the city/town and census tract measures and the risk of fatal and non-fatal assault injuries (total and firearm-only); these models adjusted for covariates, and included random effects at the census tract, city/town, and county level. For the mortality analyses, we used the observed data, given virtually no missing data (0% for most variables and <0.1% for age and race/ethnicity; Table 2). For the non-fatal injury data, we used Amelia II [63] to create five imputed data sets, since missingness ranged from 1.2 to 10.2% for the selected individual-level characteristics (Table 2). We fit all models in *R* using the glmer() function as part of the lme4 package [64] and assessed model goodness-of-fit with the AIC and BIC statistics [61, 62, 64].

Results

Between 1995 and 2010, Massachusetts encompassed 2589 fatal assault cases (1147 [55.9%] due to firearms) and 28910 non-fatal weapons-related injuries (7229 [25.0%] due to firearms) (Table 2). Cases (persons assaulted) were disproportionately concentrated, compared to the total state population, among young adults; black non-Hispanic and Hispanic persons; men; residents of large cities (population >175,000); and the counties in which these cities are located (Table 2). Whether using the census data averaged over time (Table 2), or the census-specific values (for 1990, 2000, and 2008–2012; see Additional Table 1), cases also were more likely to reside in census tracts and city/towns with higher poverty rates and with greater extreme concentrations (i.e., lower ICE values) of low- vs. high-income persons, black vs. white persons, and low-income black vs. high-income white persons, and also with higher poverty rates; they also were more likely to reside in cities (but not census tracts) with higher values for the Index of Dissimilarity (Table 2). These same groups had higher age-standardized rates for assaults compared to the on-average state rates (Additional Table 2).

We summarize key results of our multilevel analyses in Fig. 1 (fatal assaults: (a) total, (b) firearm) and Fig. 2 (non-fatal assaults: (a) total, (b) firearm); detailed tabulation of all model parameter estimates is provided in Additional Tables 3 and 4. The figures show the covariate-adjusted incidence rate ratios (IRR) and 95% confidence intervals (CI) for each type of assault for each of three ICE measures (income; race/ethnicity; income + race/ethnicity), the Index of Dissimilarity, and the continuous and categorical poverty measures; in all models, the best-off category served as the referent group. Models 1, 2, and 3 respectively included

Table 1 Index of Concentration at the Extremes (ICE), poverty, and Index of Dissimilarity (ID): variable definitions

a) Formula for the ICE and its conceptual and operational properties [14]

▪ Formula

$ICE_i = (A_i - P_i)/T_i$

where, for a given area *j*:

A_i = number of persons in the most privileged category

P_i = number of persons in the most deprived category

T_i = total count of persons belonging to population categorized in relation to the privilege/deprivation measure (e.g., income)

▪ Conceptual and operational properties

a) The ICE ranges from −1 to 1, i.e., spanning from everyone in the extreme deprived category to everyone in the extreme privileged category, and it can be modeled as both a continuous measure or as a categorical measure (e.g., quintiles).

b) Although a value of 0 theoretically could arise from two different scenarios—(1) the plausible scenario in which no persons are in either of the extremes, and (2) the implausible scenario in which an equal number of persons are in solely the two extreme categories (highly unlikely because of how spatial social polarization occurs), analyses of ICE values for census tracts within two US states (Massachusetts and New York) and their largest cities (Boston and New York City) demonstrated that only the first scenario was operative [19, 21].

c) Conceptual and operational features of the ICE:

• The ICE avoids well-known problems of colinearity that occur when analyses try to employ, simultaneously, separate measures of neighborhood poverty and wealth, which typically are highly (and inversely) correlated [14, 44, 45], as would also be the case for models that jointly include measures of percent white and percent black [21].

• The ICE can be computed in relation to one or multiple domains of privilege and deprivation, e.g., combine data on income and race/ethnicity [19–21].

• In contrast to the Gini Index (for income inequality) and Index of Dissimilarity (for racial segregation), which cannot be meaningfully used at lower levels of geography on account of spatial social segregation [14, 44], the ICE can meaningfully be employed for both smaller and larger geographic units (e.g., census tract and city/town) [14–21].

b) Conceptual and operational definition of the ICE measures, the poverty measure, and the Index of Dissimilarity, using US census data (1990 and 2000) [40–42] and American Community Survey (ACS) data (2008–2012) [40, 41]

Metric	Conceptual contrast: privilege vs. disprivilege	How computed: numerator and denominator	US census variables	ACS variables
ICE				
Income	Economic residential segregation: extreme high income vs. extreme low income	*Operational*: ((*N* of persons in high-income households) – (*N* of persons in low income households) / total population with household income data *Conceptual*: cut-points for high and low income were respectively set at the 20th vs. 80th US household income percentiles [46], which are cut-points typically used in analyses of income inequality [1, 2, 12, 47], and which for 2010 respectively were <$25,000 and ≥$100,000 [46].	1990: P80 2000: P80	B19001
Race/ethnicity	Racial residential segregation: white (high racial privilege) vs. black (low racial privilege)	*Operational*: ((*N* of persons self-identified as "white non-Hispanic") − (*N* of persons self-identified as "black non-Hispanic")) / total population with race/ethnicity data *Conceptual*: we selected these two groups [19–21] as representing extreme categories of racial privilege and disprivilege in the United States and for whom racial residential segregation has been most extreme [5–7, 37, 48, 49].	1990: P12 2000: P7	B03002
Income + race/ethnicity	Racialized economic residential segregation: high racial privilege + high income vs. low income and low racial privilege	*Operational*: ((*N* of persons self-identified as "white non-Hispanic" with high income) − (*N* of persons self-identified as "black alone" with low-income)) / total population with race/ethnicity and household income data Note: the US census provides data on income only for persons self-identified as "black alone" (i.e., did not check boxes for any other racial/ethnic groups), not for "black non-Hispanic [40–42]." *Conceptual*: As stated by Massey in 2014, low-income black versus high-income white persons "continue to occupy opposite ends of the socio-economic spectrum in the USA [50 (p. 324)]," and the construct of racialized economic segregation [19–21] captures the empirical reality of the socially structured co-determination of these forms of spatial social polarization [5, 6, 28]. The high-income and low-income cut-points were the same as employed for the ICE for income (20th vs. 80th percentile for US household income).	1990: P80 2000: P80	B19001

Table 1 (continued)

Index of Dissimilarity	Racial residential segregation	*Operational*: $D = [0.5\ \Sigma\ \lvert(b/B) - (w/W)\rvert] * 100$ where $b = N$ of black persons in smaller areal unit (e.g., census block group) and $B = N$ of black persons in the larger areal unit (e.g., census tract or city); w and W are corresponding values for the white population [7]. In our study, we used the block group as the smaller areal unit for computing both the census tract and city measures. *Conceptual*: The Index of Dissimilarity is the most commonly employed measure of residential segregation, including within public health literature, and is main measure employed by the US Census Bureau [7–11], It is a measure of the unequal distribution of the specified social groups across sub-units areas within a larger area (e.g., census tracts or neighborhoods within a city). High values indicate the two groups share no sub-units areas in common, and low values indicate that the all sub-unit areas include the same relative numbers of the two groups included in the larger area [7].	1990: P12 2000: P7	B03002
Poverty	Economic deprivation	*Operational*: (number of persons below the US poverty level/number of persons for whom the US poverty level is determined). *Conceptual*: To enable comparison to other population data, including public health data, widely analyzed in relation to the US poverty level, we computed the proportion of population below the poverty line as defined by the US census [43, 44]. The US poverty threshold was first devised in the mid-1960s in relation to the cost of what was termed an "economy food plan," which took into account the number and age of persons supported by the household income; it subsequently has been adjusted annually for inflation [51, 52]. The US census defines "poverty areas" to be ones in which ≥20% of the population is below the US poverty line [53, 54], with conventional cut-points used in public health monitoring comprising <5%, 5 to <10%, 10 to <15%, 15 to <20%, and ≥20% [44].	1990: P117 2000: P087	B17001

only the census tract measures, only the city/town measures, and the measures for both levels. Covariates comprised the cases' age, race/ethnicity, gender, year of assault, and city/town population size; all models included random intercepts for census tract, city/town, and county.

As shown in Figs. 1 and 2, two central findings stand out. First, risk gradients were both steeper and more consistent, for each measure of segregation and poverty, for the census tract as compared to the city/town measures. Moreover, in models containing both levels, independent strong social gradients consistently occurred only for the census tract measures. Second, at both geographic levels, the steepest social gradients were consistently observed for the ICE for racialized economic segregation, followed by the ICE for income and the poverty measure. By contrast, the ICE for race/ethnicity exhibited a risk gradient only at the census tract level, and the Index of Dissimilarity showed no associations at either level.

Illustrating these patterns are the results for total fatal assaults (Fig. 1, panel a; see also Additional Table 3). For these models, the covariate-adjusted IRR equaled (a) for the ICE for income + race/ethnicity, 3.96 (95% CI 3.10, 5.06) at the census tract level vs. 3.13 (95% CI 2.29, 4.26) at the city/town level; (b) for the ICE for income, 3.26 (95% CI 2.58, 4.14) at the census tract level vs. 3.26 (95% CI 2.42, 4.39) at the city/town level; (c) for poverty, 3.14 (95% CI 2.47, 3.99) at the census tract level vs. 2.29 (95% CI 1.64, 3.19) at the city/town level; (d) for the ICE for race/ethnicity, 2.90 (95% CI 2.21, 3.81) at the census tract level vs. 1.96 (95% CI 1.33, 2.90) at the city/town level; and (e) for the Index of Dissimilarity, only 0.93 (95% CI 0.79, 1.11) at the census tract level and 0.99 (95% CI 0.72, 1.35) at the city/town level. In model 3, which included both the census tract and city/town levels, the largest IRR, comparing the worst-off to best-off quintile, occurred for the ICE for race/ethnicity and income, and was greater for the census tract level (IRR 3.29; 95% CI 2.43, 4.46) vs. the city/town level (IRR 1.61; 95% CI 1.12, 2.32).

Table 2 Fatal and non-fatal assaults and total population: individual, census tract, and city/town characteristics, Massachusetts, 1995–2010

Variable	Total (MA)	Fatal assault cases		Non-fatal, weapons-related assault cases	
		All mechanisms	Firearm only	Firearm + sharp instrument	Firearm only
Total population count: *N*	6,390,611	2589	1447	28,910	7229
Age (years):					
Continuous: mean (SD)		30.7 (15.4)	27.9 (11.4)	27.4 (10.4)	24.7 (9.6)
Categorical (year): *N* (%)					
<10	800,148 (12.5%)	108 (4.2%)	10 (0.7%)	88 (0.3%)	50 (0.7%)
10–14	414,912 (6.5%)	41 (1.6%)	24 (1.7%)	529 (1.8%)	231 (3.3%)
15–19	444,315 (7%)	386 (14.9%)	287 (19.8%)	5948 (20.6%)	1955 (28.3%)
20–24	435,559 (6.8%)	568 (23.0%)	402 (27.8%)	7432 (25.7%)	2094 (30.3%)
25–29	448,707 (7%)	383 (14.8%)	258 (17.8%)	4682 (16.2%)	1126 (16.3%)
30–34	469,245 (7.3%)	254 (9.8%)	147 (10.2%)	3186 (11.0%)	560 (8.1%)
35–54	1,884,859 (29.5%)	633 (24.4%)	261 (18.0%)	5697 (19.7%)	779 (11.3%)
55–74	1,082,980 (16.9%)	171 (6.6%)	54 (3.7%)	495 (1.7%)	107 (1.6%)
75+	43,0291 (6.7%)	42 (1.6%)	3 (0.2%)	36 (0.1%)	10 (0.1%)
(unknown)	0 (0%)	3 (0.1%)	1 (0.1%)	817 (2.8%)	317 (4.1%)
Race/ethnicity: *N* (%)[a]					
White non-Hispanic	5,374,504 (81.4%)	829 (34.6%)	330 (22.8%)	8737 (34.0%)	1207 (18.6%)
Black non-Hispanic	383,437 (6.0%)	973 (40.6%)	745 (51.5%)	9184 (35.7%)	3333 (51.3%)
Hispanic	479,296 (7.5%)	525 (21.9%)	328 (22.7%)	7154 (27.8%)	1779 (27.4%)
Asian and Pacific Islander non-Hispanic	287,577 (4.5%)	61 (2.5%)	38 (2.6%)	585 (2.3%)	167 (2.6%)
American Indian/ Alaska Native	12,781 (0.2%)	6 (0.3%)	5 (0.4%)	34 (0.1%)	6 (0.1%)
(unknown)	0 (0%)	3 (0.1%)	2 (0.1%)	3216 (11.1%)	737 (10.2%)
Gender: *N* (%)					
Men	3,082,622 (48.2%)	2012 (77.7%)	1277 (88.3%)	24,434 (87.1%)	6384 (91.1%)
Women	3,307,990 (51.8%)	577 (22.3%)	170 (11.7%)	3632 (12.9%)	621 (8.9%)
(unknown)	0 (0%)	0 (0%)	0 (0%)	844 (2.9%)	224 (3.1%)
Date of assault:					
Continuous: mean (SD)		2003 (5)	2003 (5)	2003 (5)	2003 (5)
Categorical (year): *N* (%)					
1995–1999	6,249,295 (32.6%)	756 (29.2%)	382 (26.4%)	8938 (31.4%)	1909 (26.7%)
2000–2004	6,391,397 (33.3%)	758 (29.3%)	416 (28.7%)	8376 (29.4%)	2057 (28.8%)
2005–2010	6,507,721 (34.0%)	1075 (41.5%)	649 (44.9%)	11,199 (39.3%)	3179 (44.5%)
(unknown)	0 (0%)	0 (0%)	0 (0%)	397 (1.4%)	84 (1.2%)
County of residence: *N* (%)					
Barnstable	213,147 (3.3%)	47 (1.8%)	14 (1%)	417 (1.5%)	60 (0.9%)
Berkshire	131,990 (2.1%)	22 (0.9%)	7 (0.5%)	369 (1.4%)	63 (1.0%)
Bristol	544,589 (8.5%)	185 (7.2%)	91 (6.3%)	2930 (10.7%)	557 (8.4%)
Dukes	16,073 (0.3%)	2 (0.1%)	0 (0%)	8 (0%)	0 (0%)
Essex	736,933 (11.5%)	239 (9.2%)	116 (8.0%)	2843 (10.4%)	597 (9.0%)
Franklin	71,327 (1.1%)	13 (0.5%)	4 (0.3%)	112 (0.4%)	12 (0.2%)
Hampden	463,249 (7.2%)	309 (11.9%)	164 (11.3%)	3650 (13.3%)	985 (14.9%)
Hampshire	157,287 (2.5%)	15 (0.6%)	3 (0.2%)	171 (0.6%)	26 (0.4%)
Middlesex	1,495,070 (23.4%)	276 (10.7%)	126 (8.7%)	2890 (10.5%)	489 (7.4%)

Table 2 (continued)

Variable	Total (MA)	Fatal assault cases		Non-fatal, weapons-related assault cases	
		All mechanisms	Firearm only	Firearm + sharp instrument	Firearm only
Nantucket	9771 (0.2%)	2 (0.1%)	0 (0%)	13 (0.1%)	0 (0.0%)
Norfolk	666,212 (10.4%)	104 (4.0%)	45 (3.1%)	910 (3.3%)	149 (2.3%)
Plymouth	48,941 (7.7%)	182 (7.0%)	111 (7.7%)	1987 (7.3%)	574 (8.7%)
Suffolk	717,501 (11.2%)	979 (37.8%)	663 (45.8%)	8778 (32.0%)	2596 (39.2%)
Worcester	790,428 (12.4%)	214 (8.3%)	104 (7.2%)	2340 (8.5%)	520 (7.9%)
(unknown)	0 (0%)	0 (0%)	0 (0%)	1492 (5.2%)	601 (8.3%)
Residence by city/town size[b]: N (%)					
Group 1: population ≥175,000	772,223 (12.1%)	1037 (40.1%)	703 (48.6%)	9021 (32.9%)	2798 (42.2%)
Group 2: population 75,000 to <175,000	1,051,132 (16.4%)	739 (28.5%)	424 (29.3%)	9611 (35.1%)	2404 (36.3%)
Group 3: population 50,000 to <75,000	670,077 (10.5%)	167 (6.5%)	57 (3.9%)	2118 (7.7%)	322 (4.9%)
Group 4: population 25,000 to <50,000	1,581,206 (24.7%)	346 (13.4%)	161 (11.1%)	4069 (14.8%)	750 (11.3%)
Group 5: population <25,000	2,304,038 (36.1%)	300 (11.6%)	102 (7.1%)	2599 (9.5%)	354 (5.3%)
(unknown)	0 (0%)	0 (0%)	0 (0%)	1492 (5.2%)	601 (8.3%)
City/town characteristics: Average (1990–2010)[b]					
City/towns: N (%)	313 (100%)				
(unknown)	0 (0%)				
City/town: % below poverty: mean (SD)	6.3% (4.4)	16.3% (6.5)	17.4% (6.0)	1492 (5.2%)	601 (8.3%)
City/town: Index of Concentration at the Extreme (ICE):					
ICE: income (low vs. high income)	0.20 (0.21)	0.00 (0.15)	−0.02 (0.13)	−0.03 (0.14)	−0.04 (0.13)
ICE: race/ethnicity (black vs. white)	0.91 (0.11)	0.52 (0.26)	0.47 (0.24)	0.54 (0.25)	0.47 (0.23)
ICE: race/ethnicity + income (black low income vs. white high income)	0.33 (0.14)	0.16 (0.11)	0.15 (0.01)	0.15 (0.10)	0.13 (0.09)
Index of Dissimilarity (black vs. white)	43.3 (25.7)	59.0 (14.9)	60.9 (15.2)	57.1 (13.9)	58.8 (14.6)
Census tract (CT) characteristics: Average (1990–2010)					
AVERAGE (1990–2010)					
CT: N (%)	1478 (100%)				
(unknown)		18 (0.7%)	9 (0.7%)	1492 (5.2%)	601 (8.3%)
CT % below poverty: mean (SD)	10.9% (10.7)	20.2% (12.9)	22.0% (12.5)	21.1% (12.7)	23.2% (12.6)
CT Index of Concentration at the Extreme (ICE):					
ICE: income (low vs. high income)	0.11 (0.27)	−0.09 (0.25)	−0.12 (0.24)	−0.12 (0.24)	−0.15 (0.24)
ICE: race/ethnicity (black vs. white)	0.75 (0.33)	0.29 (0.58)	0.15 (0.60)	0.37 (0.52)	0.20 (0.55)

Table 2 (continued)

Variable	Total (MA)	Fatal assault cases		Non-fatal, weapons-related assault cases	
		All mechanisms	Firearm only	Firearm + sharp instrument	Firearm only
ICE: race/ethnicity + income (black low income vs. white high income)	0.27 (0.20)	0.07 (0.22)	0.02 (0.22)	0.08 (0.19)	0.02 (0.20)
Index of Dissimilarity (black vs. white)	35.5 (23.7)	34.9 (16.2)	34.4 (16.5)	34.4 (16.3)	33.8 (16.3)
Fatal assault					
Cause of death[c]: N (%)	2397 (100%)				
Homicide due to firearm (ICD-9: E965.0-E965.4; ICD-10: X93-X95)	1417 (54.7%)				
Death due to legal intervention ((ICD-9: E970 (firearm) + E971-E977 (other); ICD-10: Y935 (firearm) + Y351-Y357 (other)	33 (1.3%)				
All other assault deaths: (ICD-9: E960-E964, E965.5-E969; ICD-10: X85-X92, X96-Y08)	1139 (44.0%)				

Percent distribution is based on observed values; percent for unknown is based on total population

[a] Because census methodology for recording race/ethnicity changed between 1995 and 2010, we derived proportions for each race/ethnicity category during this period from the National Center for Health Statistic's Bridged-Race Population Estimates [65]. We included decedents classified as Cape Verdean ($N = 68$) in the non-Hispanic black category

[b] Towns by population size, using cut-points employed in the Massachusetts Weapons-Related Injury Surveillance System [30]: Group 1: population ≥175,00 (Boston, Worcester); Group 2: population 75,000 to <175,000 (Brockton, Cambridge, Fall River, Lawrence, Lowell, Lynn, New Bedford, Newton, Quincy, Somerville, Springfield); Group 3: population 50,000 to <75,000 (Brookline, Chicopee, Framingham, Haverhill, Malden, Medford, Peabody, Plymouth, Revere, Taunton, Waltham, Weymouth); Group 4: population 25,000 to <50,000 (Natick, North Andover, North Attleborough, Northampton, Norwood, Pittsfield, Randolph, Salem, Saugus, Shrewsbury, Stoughton, Tewksbury, Wakefield, Watertown, West Springfield, Westfield, Woburn); and Group 5: population <25,000 (Abington, Acushnet, Amesbury, Ashby, Athol, Auburn, Avon, Barre, Bedford, Belmont, Blandford, Bourne, Boxford, Brewster, Brimfield, Brookfield, Carver, Charlton, Chatham, Cheshire, Clinton, Colrain, Dedham, Dennis, Dighton, Douglas, Dudley, East Bridgewater, Easthampton, Easton, Fairhaven, Foxborough, Freetown, Gardner, Gosnold, Grafton, Granby, Great Barrington, Greenfield, Groton, Hampden, Hanover, Hanson, Harwich, Hingham, Holbrook, Holden, Hopkinton, Hudson, Hull, Kingston, Lakeville, Leicester, Lincoln, Ludlow, Lunenburg, Lynnfield, Mansfield, Mashpee, Mattapoisett, Mendon, Middleborough, Millbury, Monson, Montague, Nahant, Nantucket, Newbury, Newburyport, Norfolk, North Adams, North Reading, Northbridge, Norton, Oak Bluffs, Palmer, Pelham, Plainville, Provincetown, Raynham, Reading, Rockland, Rutland, Salisbury, Sandwich, Shelburne, Shirley, Shutesbury, Somerset, Southbridge, Spencer, Stoneham, Stow, Sturbridge, Sudbury, Sutton, Swampscott, Swansea, Templeton, Townsend, Truro, Tyngsborough, Upton, Uxbridge, Wales, Walpole, Ware, Wareham, Warren, Webster, Wenham, West Bridgewater, West Brookfield, Westborough, Westford, Westminster, Weston, Westport, Westwood, Whitman, Wilbraham, Wilmington, Winchendon, Winchester, Winthrop, Yarmouth). Note: Using 2010 Census boundaries, 59 of 351 Massachusetts towns were nested within census tracts containing ≥2 towns. To ensure that these towns conformed to the multilevel structure of the rest of the data (i.e., ≥1 census tract nested within a town), we aggregated these 59 towns into 21 "super-towns"

[c] ICD-9 codes used for 1979–1998 and ICD-10 codes used for 1999–2010 [32, 38]

Analogous patterns were observed for fatal assaults restricted to firearm-only (Fig. 1, panel b; Additional Table 3) and for the non-fatal weapons-related assaults (total and firearm-only) (Fig. 2, Additional Table 4). Thus, as illustrated by the model 3 results, for fatal firearm assaults, the IRR for the ICE for race/ethnicity and income equaled 2.87 (95% CI 1.84, 4.49) for the census tract measure but was not distinguishable from 1 for the city/town measure (IRR 1.34; 95% CI 0.78, 2.29). For non-fatal weapons-related assaults, this IRR equaled 3.28 (95% CI 2.84, 3.78) at the census

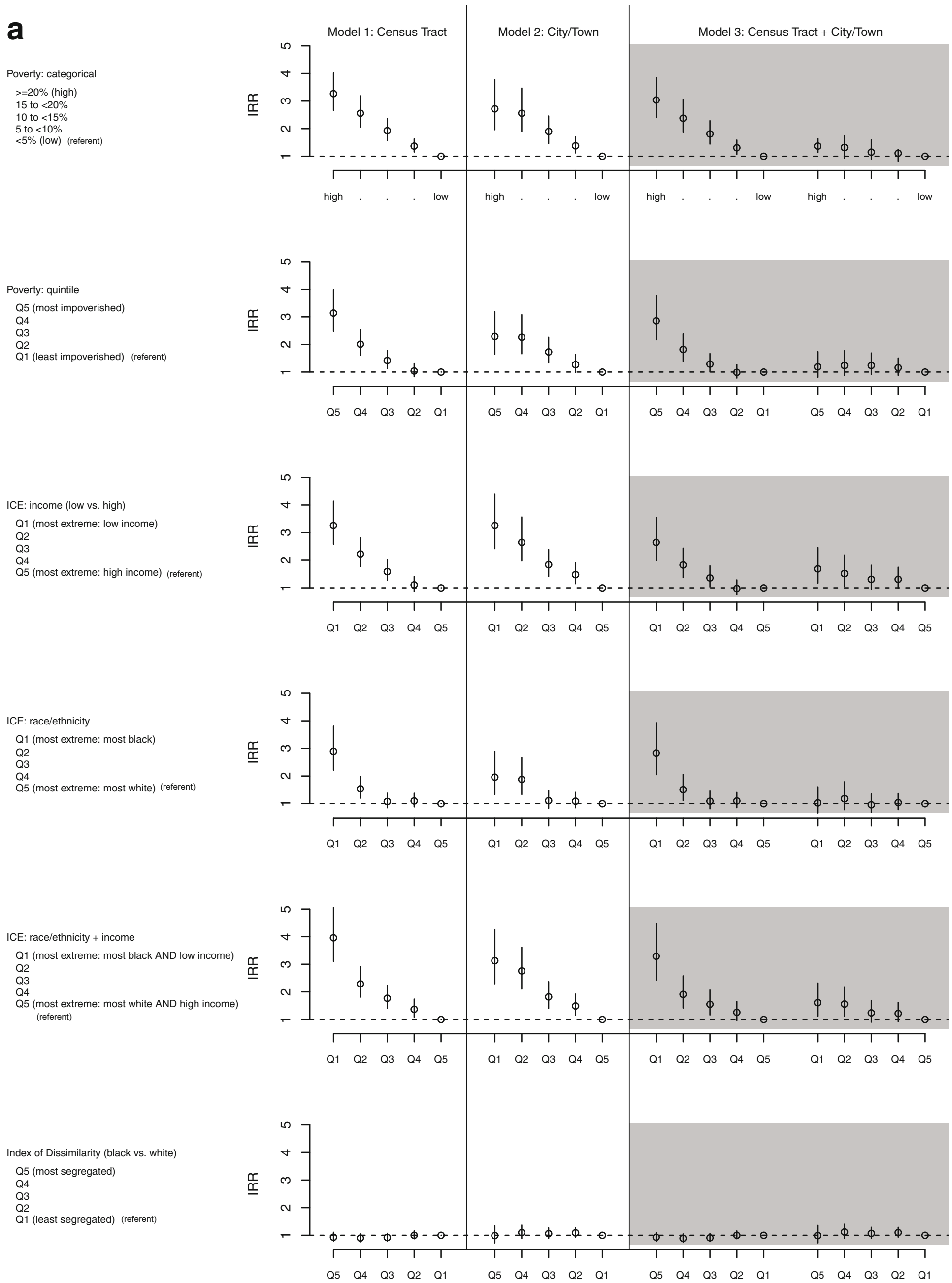

Fig. 1 **a** Total fatal assault rate ratios: ICE, poverty, and ID, MA CTs and cities/towns, 1995–2010. **b** Firearm fatal assault rate ratios: ICE, poverty, and ID, MA CTs and cities/towns, 1995–2010

tract level vs. only 1.38 (95% CI 1.11, 1.70) at the city/town level. For non-fatal firearm-related assaults, this IRR equaled 4.61 (95% CI 3.48, 6.11) at the census tract level, but only 1.52 (95% CI 1.05, 2.21) at the city/town level.

Discussion

In accord with our a priori hypotheses, in Massachusetts (1995–2010), consistently steeper gradients for risk of fatal and non-fatal assaults were detected using

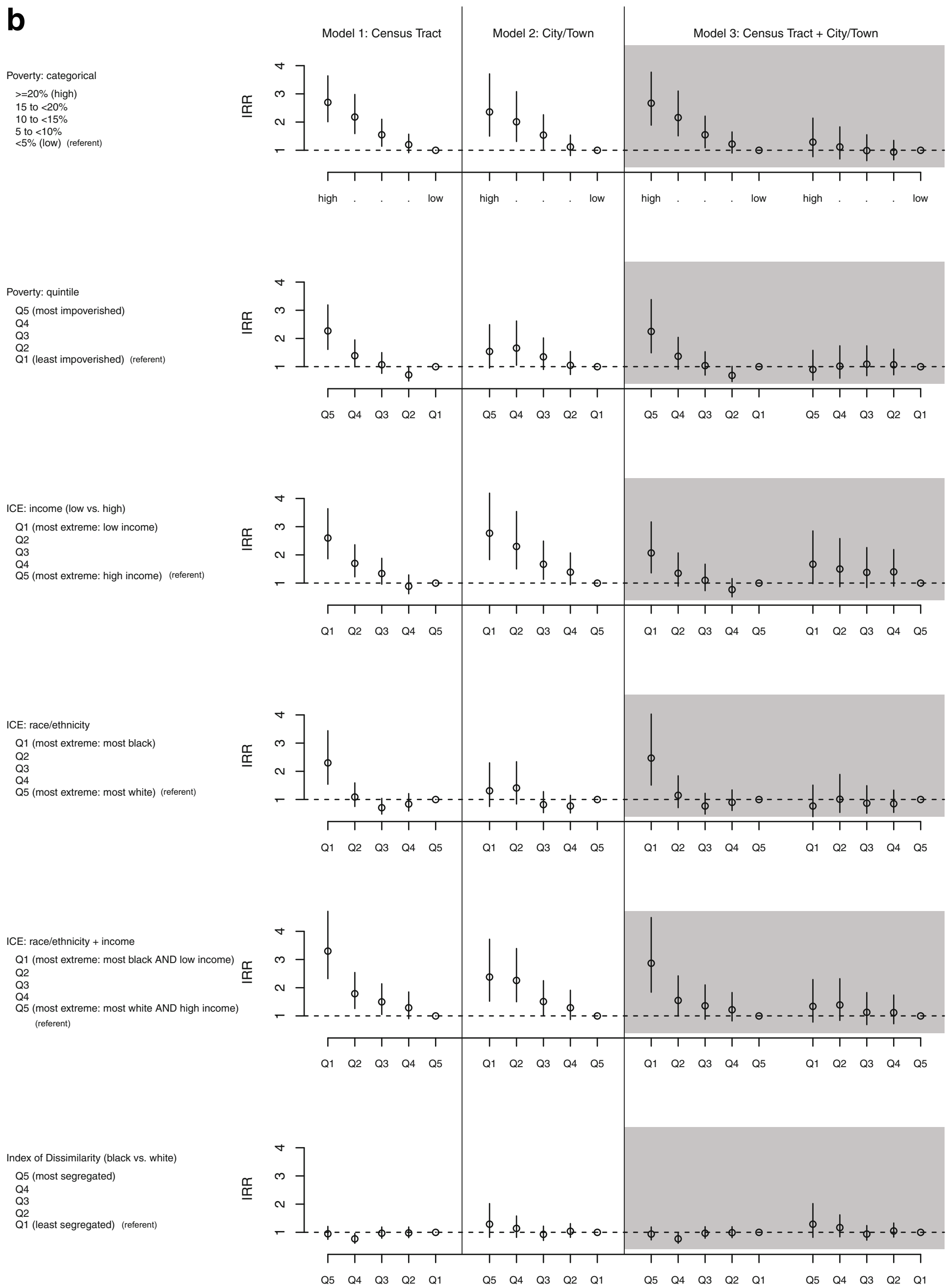

Fig. 1 (continued)

segregation measures computed at the census tract as compared to city/town level. Additionally, consistently greater risk gradients were detected with the ICE measures for racialized economic segregation, as compared to (a) the ICE for income and the ICE for race/ethnicity, and (b) the poverty measure and the Index of Dissimilarity. Together, these results suggest that conventional approaches solely employing city or regional measures of racial segregation (including the Index of Dissimilarity [8–11]) are likely to underestimate the association between fatal and non-fatal assaults and residential segregation.

Regarding study strengths and limitations, our investigation used high-quality statewide vital statistics and

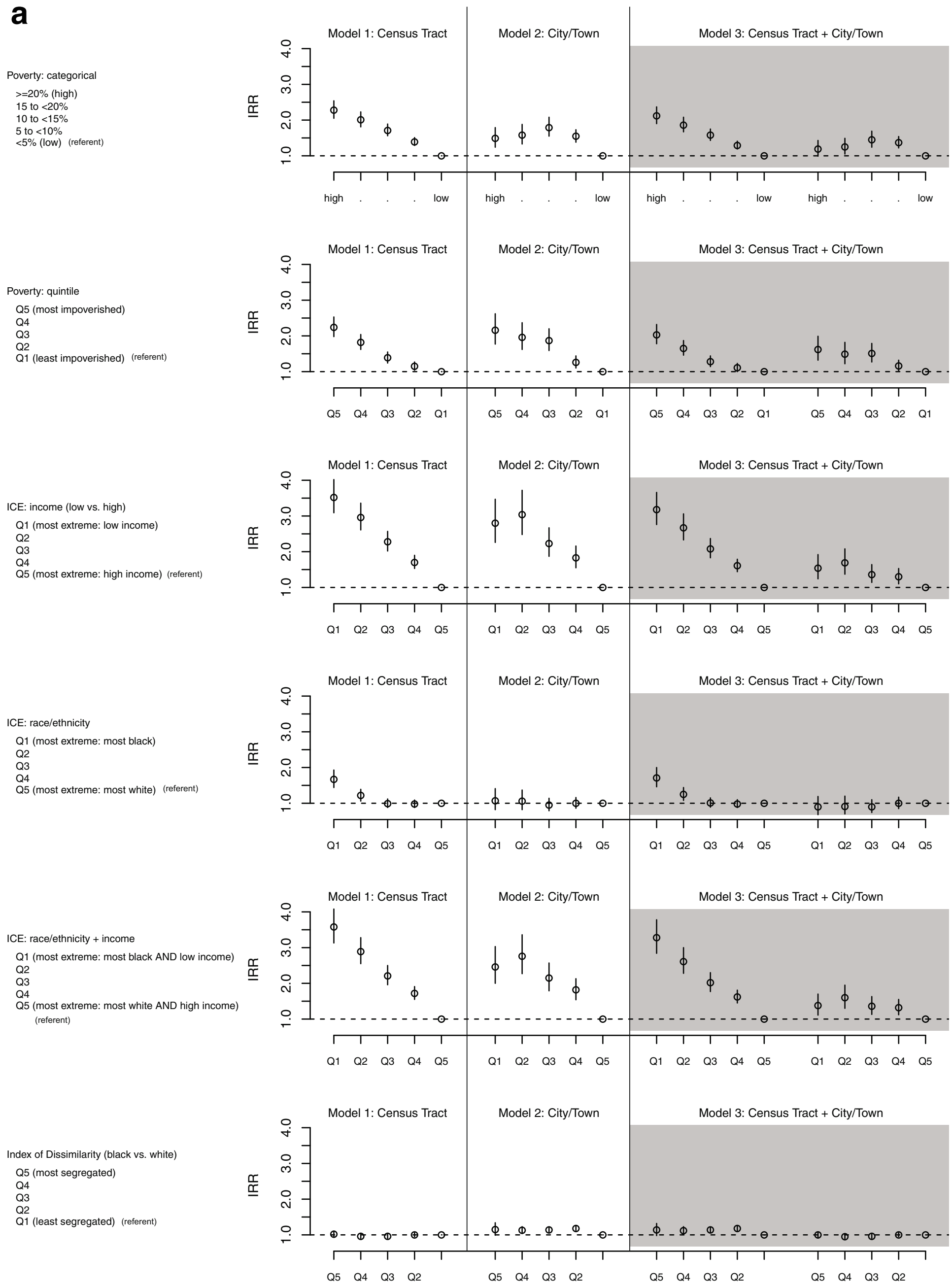

Fig. 2 **a** Non-fatal weapons-related assault rate ratios: ICE, poverty, and ID, MA CTs and cities/towns, 1995–2010. **b** Non-fatal firearm assault rate ratios: ICE, poverty, and ID, MA CTs and city/towns, 1995–2010

surveillance data [32–34] and had over 80% power (two-sided alpha = 0.05) to test our a priori hypotheses. By design, our study was not a causal analysis, but instead was intended to generate novel descriptive data that could inform public health monitoring [21, 44] and place-based interventions [66], as well as spark more complex causal investigations. Possible foci for research on the mechanisms that both generate residential segregation and their health impacts might be, in the case of assaults, the range of institutional and interpersonal practices that protect racial and economic privilege [1–14], along with US policies that permit firearms to

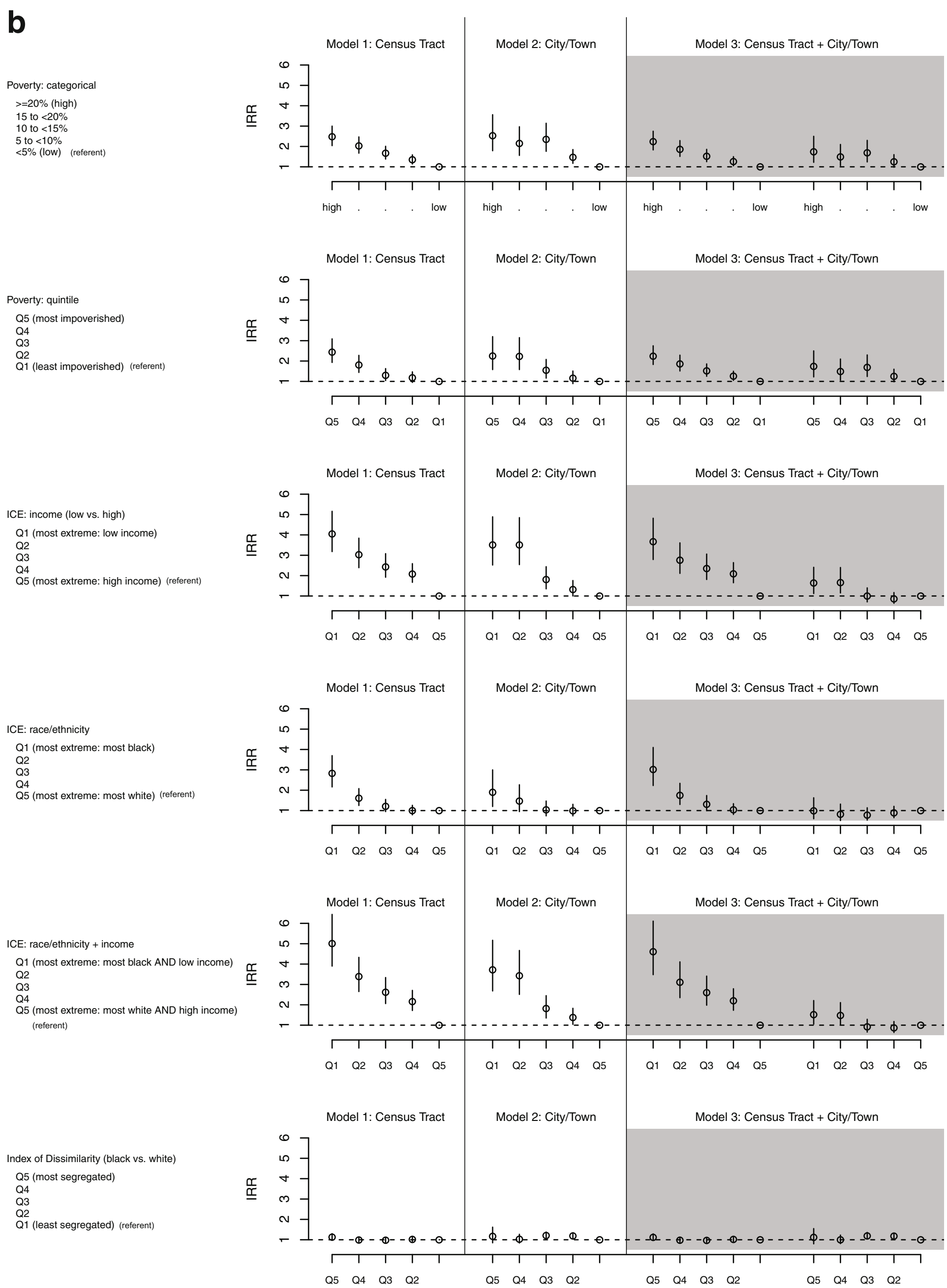

Fig. 2 (continued)

be widely available [26–28]. Supporting such an approach is a new US national multilevel analysis, which found that "the percentage black plays no detectable role net of controls, in predicting violent crime in cities with a black mayor, significant black elected representation, a civilian police review board, high percentages of a Democratic voting electorate, high rates of minority advocacy organizations, and post-civil rights histories of rioting [67]." Notably, none of these types of contextual measures or even more limited measures of racial segregation were included in the 2016 *Epidemiologic Reviews* volume focused on understanding and preventing gun violence [68].

Lending credence to our findings, our results for the ICE measures were in accord with those of our three prior city-specific analyses, conducted within either Boston or New York City [19–21]. All three studies found that (1) ICE measures combining data on race/ethnicity and income typically detected sharper social gradients in health outcomes as compared to (a) the poverty rate, and (b) ICE measures for income, and (2) gradients detected at the census tract level exceeded those detected at higher levels (e.g., community district) [19–21]. Because these studies were each based within only one city, however, they could not contrast use of the ICE at the census tract versus city/town level.

We recognize that the steeper mortality gradients observed using spatial segregation measures computed at the census tract compared to city/town level should not be surprising, since aggregation typically reduces (and cannot increase) variation [45, 61]. Nor should it be surprising that a measure that jointly quantifies racial/ethnic and economic residential segregation reveals larger inequities than segregation measures which focus only on racial/ethnic segregation or only on economic segregation [19–21]. What is striking, however, is that the most common measures of residential segregation, including those used in public health and social science research, have been single-focus (e.g., Index of Dissimilarity for race/ethnicity only) and have primarily been computed at the city level or higher [7–11].

We acknowledge that data for one state in the USA are not representative of all states and also that more comprehensive analyses should assess US residential racial/ethnic segregation for not only the US black vs. white non-Hispanic population but for other US racial/ethnic groups as well, e.g., Hispanic, Asian and Pacific Islander, and American Indian and Alaska Native vs. white non-Hispanic [7, 37]. However, as explained above, Massachusetts constitutes an apt state for testing our novel study hypotheses due to both its high levels of income inequality and racial/ethnic segregation [35–37] and its racial/ethnic and economic inequities in fatal and non-fatal assaults [30, 33]. Supporting use of our ICE for racialized economic segregation, within the USA, low-income black persons versus high-income white persons "continue to occupy opposite ends of the socioeconomic in the USA" [50, p. 324]. One advantage of the ICE, as contrasted to local measures of relative segregation (which compare the probability of two groups encountering each other in a given neighborhood as compared to the probability in the city overall, taking into account the composition of adjacent neighborhoods [22–25]) is that the ICE transparently measures the absolute concentration of place-based privilege and deprivation using a metric easily compared across neighborhoods, cities, and regions. Future research, in the USA and other regions and countries, could expand testing our study hypotheses to address diverse health outcomes, as well as use ICE defined in relation to additional racial/ethnic groups and also nativity, as well as in relation to wealth, education, employment, and other socioeconomic parameters.

Conclusions

In summary, our study provides empirical evidence that measures of racialized economic segregation, especially at the census tract level, may provide new insights into how segregation structures the risk of fatal and non-fatal assaults. As new place-based approaches to addressing structural determinants of health and health inequities gain traction in diverse countries [66, 69, 70], accurate estimates of the impact of residential segregation on health are needed.

CI, confidence interval; CT, census tract; ICE, Index of Concentration at the Extremes; ID, Index of Dissimilarity; MDPH, Massachusetts Department of Public Health; US, United States

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