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Traumatic brain injury mortality among U.S. children and adolescents ages 0–19 years, 1999–2017

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A B S T R A C T

Introduction: To examine recent traumatic brain injury (TBI) mortality changes among Americans aged 0–19 years by sex, age, urbanicity, state, and intent/causes of injury. *Method:* TBI mortality per 100,000 population and average annual percent changes (AAPCs), plus 95% confidence intervals (CIs) based on Joinpoint regression models. *Results:* Age-adjusted TBI mortality among Americans aged 0–19 years declined consistently, though at varying rates between 1999 and 2013 (AAPC = −4.8%, 95%CI: −6.3%, −3.2%), and then significantly increased from 4.42 per 100,000 population in 2013 to 5.17 per 100,000 population in 2017 (AAPC = 3.4%, 95% CI: 1.7%, 5.1%). During the study time period, boys, rural children, and youth aged 15–19 years had higher TBI mortality rates than girls, urban children, and younger children, respectively. TBI mortality from unintentional transport crashes decreased substantially in all age groups between 1999 and 2017, and especially from 1999 to 2010. TBI mortality from suicide increased significantly from 2008 to 2017 in the 10–14-year age group (AAPC = 14.6%, 95% CI: 12.6%, 16.6%) and from 2007 to 2017 in the 15–19-year age group (AAPC = 6.3%, 95% CI: 3.8%, 8.7%). Unintentional transport crashes were the leading cause of TBI-related mortality in 46 states in 1999, but by 2017, suicide became the first leading cause in 14 states. *Conclusions:* Pediatric TBI mortality declined consistently between 1999 and 2013 and increased significantly from 2013 to 2017, driven primarily by the mortality decrease from unintentional transport crashes and increase in suicide mortality. The spectrum of leading causes of pediatric TBI mortality changed across age groups and over time from 1999 to 2017. *Practical Applications:* TBI mortality increases in the United States since 2013 are driven primarily by increasing suicide rates, a trend that merits the attention of policy-makers and injury researchers. Action should be taken to curb growing TBI mortality rates among adolescents aged 10–19 years.

1. Introduction

Traumatic brain injury (TBI) is a major cause of child mortality and morbidity. An estimated 475,000 children aged 0–14 years old sustain a TBI each year, 37,000 children required hospitalization, and about 2,685 children died from TBI between 1995 and 2001 in the United States (Langlois, Rutland-Brown, & Thomas, 2005). The costs of inpatient care for pediatric TBI-associated hospitalizations are estimated to exceed one billion dollars annually in the United States (Schneier, Shields, Hostetler, Xiang, & Smith, 2006).

In response to this challenge, the Centers for Disease Control and Prevention (CDC) included TBI as a priority in its national injury prevention agenda in 2009 (National Center for Injury Prevention and Control, 2009; National Center for Injury Prevention and Control, 2019) and devoted significant effort to mobilize the country for youth TBI prevention through federal and state efforts (Baldwin, Breiding, & Sleet, 2016). Initiatives included the establishment of the National Association of State Head Injury Administrators (NASHIA) (National Association of State Head Injury Administrators, 2019), the launch of the *Heads Up* initiative (https://www.cdc.gov/headsup/) and the introduction of sports concussion (Baugh, Kroshus, Bourlas, & Perry, 2014) and child-restraint laws in many jurisdictions (Bae, Anderson, Sliver, & Macinko, 2014). The results of these efforts remain unexamined, although some previous reports offer data on TBI prevalence from specific activities, such as sports and recreation (Coronado et al., 2015), blunt trauma (Quayle et al., 2014) and motor-vehicle crashes (Viano, Parenteau, Xu, & Faul, 2017). Other existing studies

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report the overall TBI trends from before 2010 (Faul, Xu, Wald, & Coronado, 2010), trends for only 1–3 year time periods (Haarbauer-Krupa, Lee, Bitsko, Zhang, & Kresnow-Sedacca, 2018; Taylor, Bell, Breiding, & Xu, 2017) and local government data (Zogg et al., 2018). We therefore conducted a longitudinal analysis to examine changes in TBI mortality among U.S. children and adolescents ages 0–19 from 1999 to 2017 by sex, urbanicity, age groups, intent/causes, and state.

2. Materials and methods

2.1. Data source

Mortality data from 1999 to 2017 were extracted from the multiple-cause-of-death public use data in the CDC Wide-ranging Online Data for Epidemiologic Research (CDC WONDER) system, an interactive web-based tool (United States Department of Health and Human Services [U.S. DHHS], 2019). Mortality rates were estimated by the National Vital Statistics System based on resident death certificates in the 50 states and District of Columbia. Cause of death was coded in accordance with the International Classification of Disease, 10th Revision (ICD-10). The denominator to calculate mortality rates was based on population data from the U.S. Census Bureau.

2.2. ICD-10 codes for traumatic brain injury

Following recommendations from the U.S. CDC (Faul et al., 2010), TBI deaths were defined as those with a TBI-related code from the ICD-10 in any position of the National Vital Statistics System (NVSS) mortality record, including: S01.0-S01.9, S02.0, S02.1, S02.3, S02.7-S02.9, S04.0, S06.0-S06.9, S07.0, S07.1, S07.8, S07.9, S09.7-S09.9, T01.0, T02.0, T04.0, T06.0, T90.1, T90.2, T90.4, T90.5, T90.8, and T90.9.

Based on preliminary analyses (not shown here), we classified child TBI into six categories by intent and external cause: (a) unintentional transport crashes (V01-V99); (b) unintentional non-transport crashes (W00-X59, Y85-Y86); (c) suicide (X72-X74, *U03, X60-X71, X75-X84, Y87.0); (d) homicide by firearm (*U01.4, X93-X95); (e) homicide by non-firearms means and their sequelae (*U01.0-*U01.3, *U01.5-*U01.9, *U02, X85-X92, X96-Y09, Y87.1); and (f) all others, including legal intervention, events of undetermined intent, complications of medical and surgical care, and other diseases. Considering it is difficult to identify suicidal TBI among children younger than 10 years old (Maris, & Canetto, 2000), we excluded intent-specific analyses for children under 10 years.

2.3. Statistical analyses

Mortality rates were age-standardized using the national projected population from the U.S. Census 2000 as the reference to eliminate the effects of age from crude rates. Joinpoint regression model was performed to identify significant inconsistencies in mortality change trends from 1999 to 2017. Joinpoint regression model is recommended to describe and distinguish changes across different time periods by examining trends in data over time (Kim, Fay, Feuer, & Midthune, 2000). Annual percent changes (APCs) and 95% confidence intervals (CIs) were calculated to quantify the magnitude and direction of mortality changes. When multiple consecutive periods with monotonic increasing or decreasing trends were identified, average annual percent changes (AAPCs) were calculated to quantify the overall trend (National Cancer Institute, 2019). When there is a single consecutive period, AAPCs equal APCs. We use AAPCs throughout the manuscript to simplify expression of the term.

We considered four demographic factors in subgroup analysis (sex, age group, urbanicity, and state). Age was divided into five groups (<1 year, 1–4 years, 5–9 years, 10–14 years, and 15–19 years) (Faul et al., 2010). The urbanicity of deaths was based on the county of the person's legal residence (U.S. Department of Health and Human Services, 2019). The six urbanization categories listed in the CDC WONDER, which are based on the 2013 NCHS Urban-Rural Classification Scheme for Counties according to the Office of Management and Budget's (OMB) February 2013 delineation of metropolitan/micropolitan statistical areas and Vintage 2012 postcensal estimates of the resident U.S. population (CDC/ National Center for Health Statistics, 2019), were combined into three groups: large central or fringe metro, medium or small metro, and non-metro. We use the terms, "large city and suburbs," "medium or small city," and "rural area" to describe the three categories. State-specific analyses were performed separately for 1999–2013 and 2013–2017 since preliminary analysis (not shown here) showed clearly distinct TBI-related mortality changes in the two time periods.

Line graphs were plotted to demonstrate mortality changes over time by sex, age group, urbanicity, and intent/cause of injury. Geographic maps demonstrated state variations in TBI mortality and mortality changes over time; the maps were graphed through Visual Basic for Application (VBA) in Microsoft Excel 2016. Joinpoint regression was conducted through Joinpoint Regression Program version 4.6.0.0. All other statistical analyses were performed using Stata/IC 12.1. Mortality changes with p values less than 0.05 were considered statistically significant.

3. Results

3.1. Overall TBI mortality

From 1999 to 2017, there were an estimated 99,796 TBI-induced deaths among children and adolescents aged 0–19 years in the United States (Fig. 1A and Online Supplementary Table 1). Age-adjusted TBI mortality substantially declined from 8.99 per 100,000 population in 1999 to 4.42 per 100,000 population in 2013 (AAPCs = −4.8%, 95% CI: −6.3%, −3.2%). Beginning in 2013, age-adjusted TBI mortality began to rise continuously, reaching 5.17 per 100,000 population in 2017 (AAPCs = 3.4%, 95% CI: 1.7 %, 5.1%) (Online Supplementary Fig. 1).

3.2. TBI mortality by sex, age group, urbanicity, and intent/causes

During 1999–2017, TBI mortality rates for males were 2.0–2.6 times the rate for females (Fig. 1A; and Online Supplementary Table 1). For males, TBI mortality declined substantially between 1999 and 2013 (AAPCs = −4.6%, 95% CI: −6.1%, −2.9%), but rose 20% between 2013 and 2017 (AAPCs = 3.8%, 95% CI: 1.7%, 5.9%); for females, TBI mortality decreased significantly between 1999 and 2010 (AAPCs = −5.8%, 95% CI: −7.0%, −4.6%) but remained nearly unchanged between 2010 and 2017 (AAPCs = −0.3%, 95% CI: −2.2%, 1.6%) (Online Supplementary Fig. 1).

Across the full study time period, adolescents aged 15–19 years had the highest TBI mortality rate among the age groups studied, followed by infants younger than 1 year, and then children aged 1–4 years, 10–14 years and 5–9 years (Fig. 1B; and Online Supplementary Table 1). TBI mortality varied across age groups from 1999 to 2017. The most notable TBI morality changes occurred among the youth aged 15–19 years, who experienced an AAPC of −5.2% (95% CI: −7.3%, −3.1%) from 1999 to 2013 and 4.8% (95% CI: 2.4%, 7.3%) from 2013 to 2017. Mortality changes were compara-

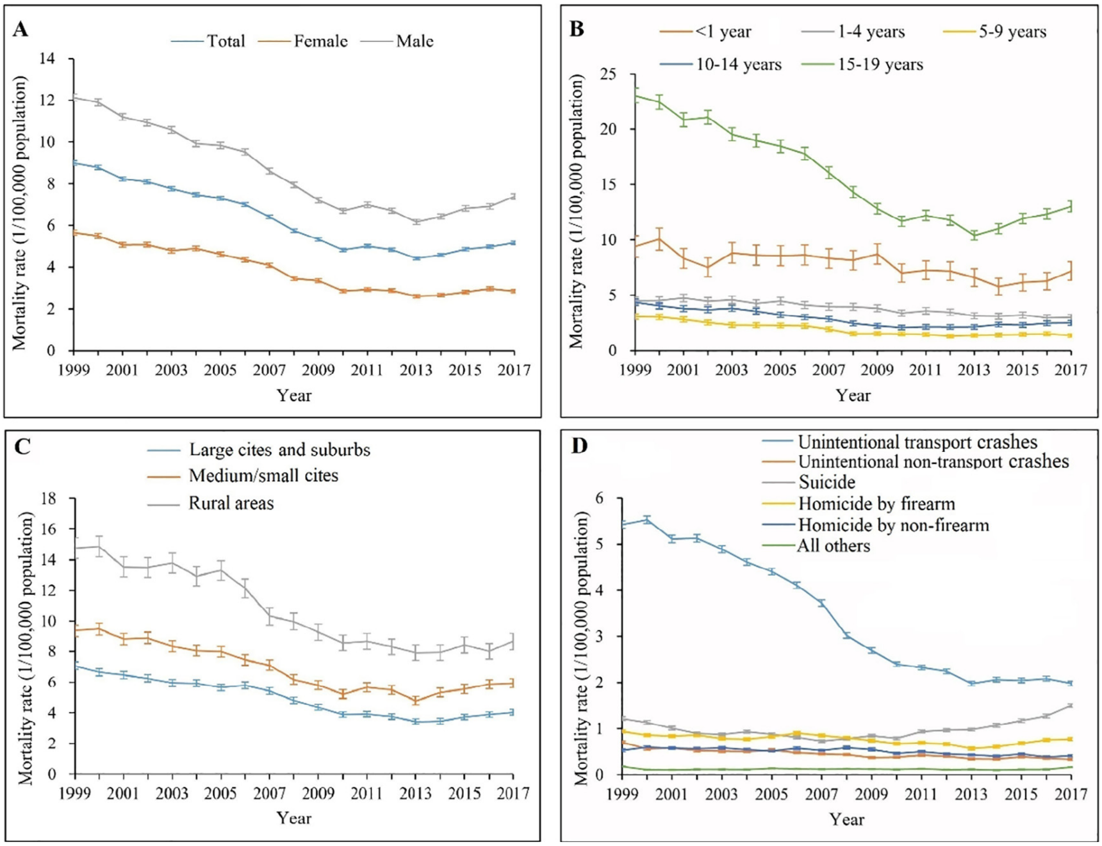

Fig. 1. Mortality rates per 100,000 population (SE) for traumatic brain injury deaths in the United States, 1999–2017. Notes: 1. By sex (panel A), by age group (panel B), by urbanicity (panel C); by intent/cause of injury (panel D); 2. Mortality rates for traumatic brain injury in panels A, C and D were age-standardized based on the 2000 U.S. census population; 3. The suicide mortality in panel D only included TBI deaths among people over 10 years old.

tively moderate in the other four age groups, although all changes were statistically significant (Online Supplementary Fig. 2).

Children and adolescents living in large cities and suburbs had much lower TBI mortality rates than youth in medium or small cities (0.7–0.8 times) and in rural areas (0.4–0.5 times) between 1999 and 2017. Trends over time were similar across all three urbanization categories, with decreases present from 1999 to 2013 and gradual increases from 2013 to 2017 (Fig. 1C; Online Supplementary Table 1; Online Supplementary Fig. 3).

Among the six intent/cause categories, unintentional transport crashes, suicide, and homicide by firearm were the three leading causes of TBI mortality from 1999 to 2017, respectively accounting for 55%, 16%, and 12% of overall TBI mortality (Fig. 1D; Online Supplementary Table 1). Mortality changes among those three leading intent/causes together dominated the change patterns of overall TBI mortality from 1999 to 2017. Specifically, TBI from unintentional transport crashes decreased from 1999 to 2017 (AAPCs = −5.7%, 95% CI: −6.9%, −4.5%); suicide TBI mortality decreased from 1999 to 2008 (AAPCs = −5.0%, 95% CI: −6.6%, −3.4%) and then increased rapidly from 2008 to 2013 (AAPCs = 7.5%, 95% CI: 5.8%, 9.2%); and homicide mortality by firearm decreased from 1999 to 2013 (AAPCs = −3.1%, 95% CI: −5.6%, −0.5%) and then increased from 2013 to 2017 (AAPCs = 7.3%, 95% CI: 3.1%, 11.7%) (Online Supplementary Fig. 4).

As shown in Fig. 2, the intent/cause spectrums for TBI mortality divided by sex and by urbanicity were fairly similar to those for overall TBI mortality (Fig. 2; Online Supplementary Tables 2–3; Figs. 5–9).

However, the intent/cause spectrum varied greatly across age groups. Homicide by non-firearm means and their sequelae was the first leading cause of TBI mortality for infants under age 1 year (58%) and the second leading cause for the 1–4-year age group (24%). In contrast, unintentional transport crashes were the leading cause of TBI mortality for the three older age groups, explaining 72%, 61% and 54% of overall mortality, respectively (Fig. 3; Online Supplementary Table 4). Over time, mortality from unintentional transport crashes dropped dramatically in all five age groups between 1999 and 2017, excepting the group of infants under 1 year, for which mortality declined first until 2014, and then increased (AAPCs = 17.8%, 95% CI: 4.5%, 32.8%) (Online Supplementary Fig. 10). Additionally, substantial increases occurred in TBI mortality from suicide among children aged 10–14 years from 2008 to 2017 (AAPCs = 14.6%, 95% CI: 12.6%, 16.6%) and adolescents aged 15–19 years from 2007 to 2017 (AAPCs = 6.3%, 95% CI: 3.8%, 8.7%), and in TBI mortality from homicide by firearm among adolescents aged 15–19 years from 2014 to 2017 (AAPCs = 12.4%, 3.2%, 22.5%) (Online Supplementary Figs. 11–12).

3.3. State variations

Year-by-year state-specific analyses revealed that age-adjusted TBI mortality rates varied widely across the U.S. states between 1999 and 2017 (3.0–7.5 times), with the highest rate detected in Mississippi in 2000 (16.75 per 100,000 population) and the lowest rate in Massachusetts in 2013 (1.04 per 100,000 population) (Fig. 4).

Between 1999 and 2013, TBI mortality dropped significantly in the 39 states for which data were available, following trends for overall TBI mortality rates (AAPCs: −0.7%–−6.9%). Seven states (Louisiana, Maryland, Missouri, Nevada, Ohio, Tennessee, and Tex-

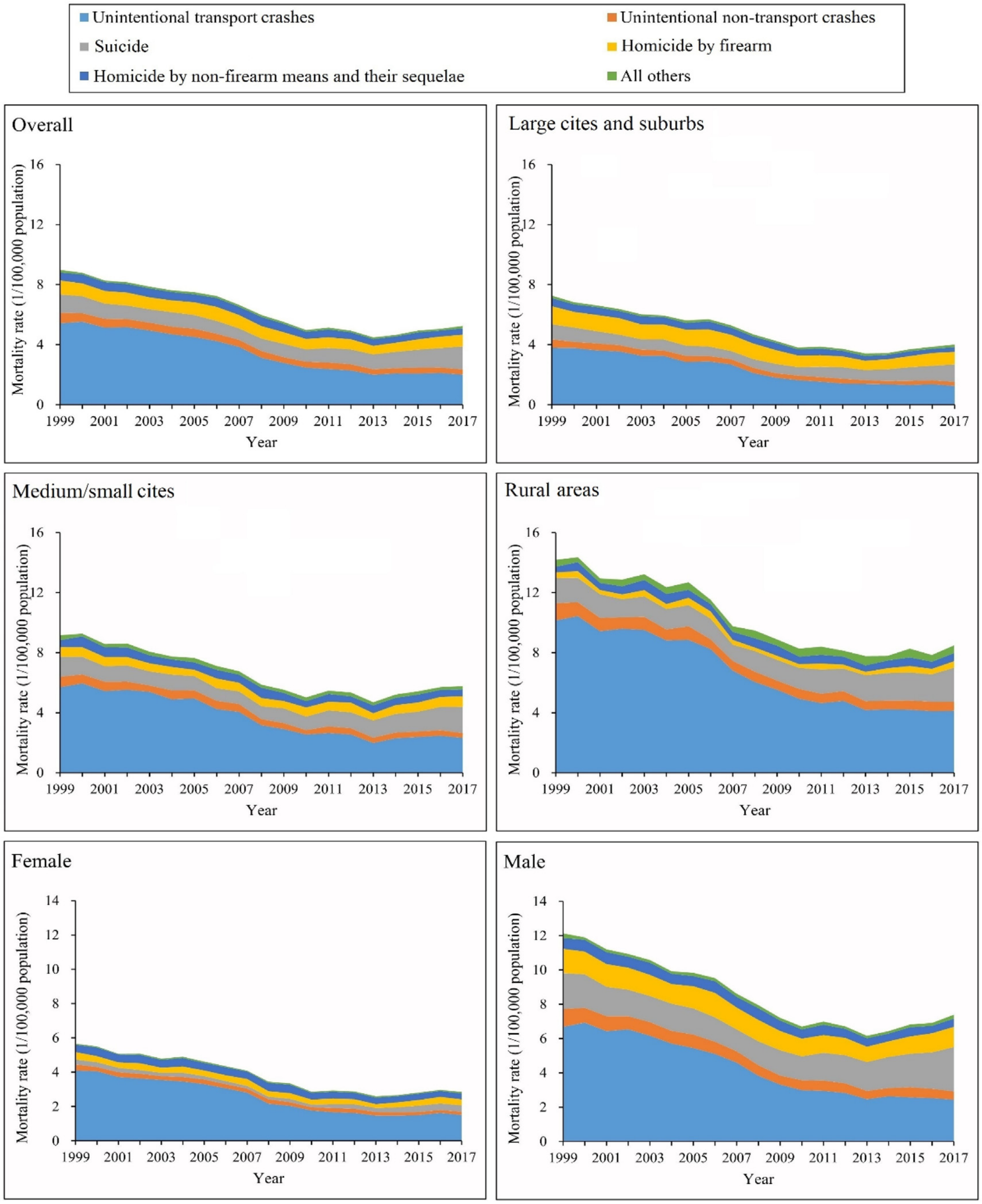

Fig. 2. Age-adjusted mortality (per 100,000 population) from traumatic brain injury by intent/cause, urbanicity and sex in the United States, 1999–2017. Notes: 1. Mortality rates for traumatic brain injury were age-standardized based on the 2000 U.S. census population; 2. Because it is difficult to identify suicidal TBI among children younger than 10 years old, the suicide related TBI mortality only included deaths among people over 10 years.

as) witnessed significant increases in TBI mortality between 2013 and 2017 (AAPCs: 3.5%–17.6%), with the greatest increases in Maryland (AAPCs = 17.6%, 95% CI: 4.3%, 32.6%) and Nevada (AAPCs = 17.1%, 95% CI: 11.4%, 23.0%) (Online Supplementary Table 5).

Across different states, the TBI mortality spectrum by intent/-cause changed over time. In 1999, unintentional transport crashes were the leading cause of TBI mortality in the 46 states for which data were available, accounting for 38%–72% of overall TBI mortality. By 2017, suicide replaced unintentional transport crashes as the leading cause in 14 states (Alaska, Arizona, Arkansas, Colorado, Idaho, Michigan, Minnesota, Montana, Nevada, New Mexico, Oklahoma, Tennessee, Texas and Utah; data were suppressed for 8 states and the District of Columbia due to confidentiality constraints in CDC WONDER) (Online Supplementary Table 6).

4. Discussion

4.1. Summary of findings

Four key findings are summarized as follows: (a) age-adjusted child and adolescent TBI mortality decreased substantially in the U.S. from 1999 to 2013, primarily driven by a mortality decrease

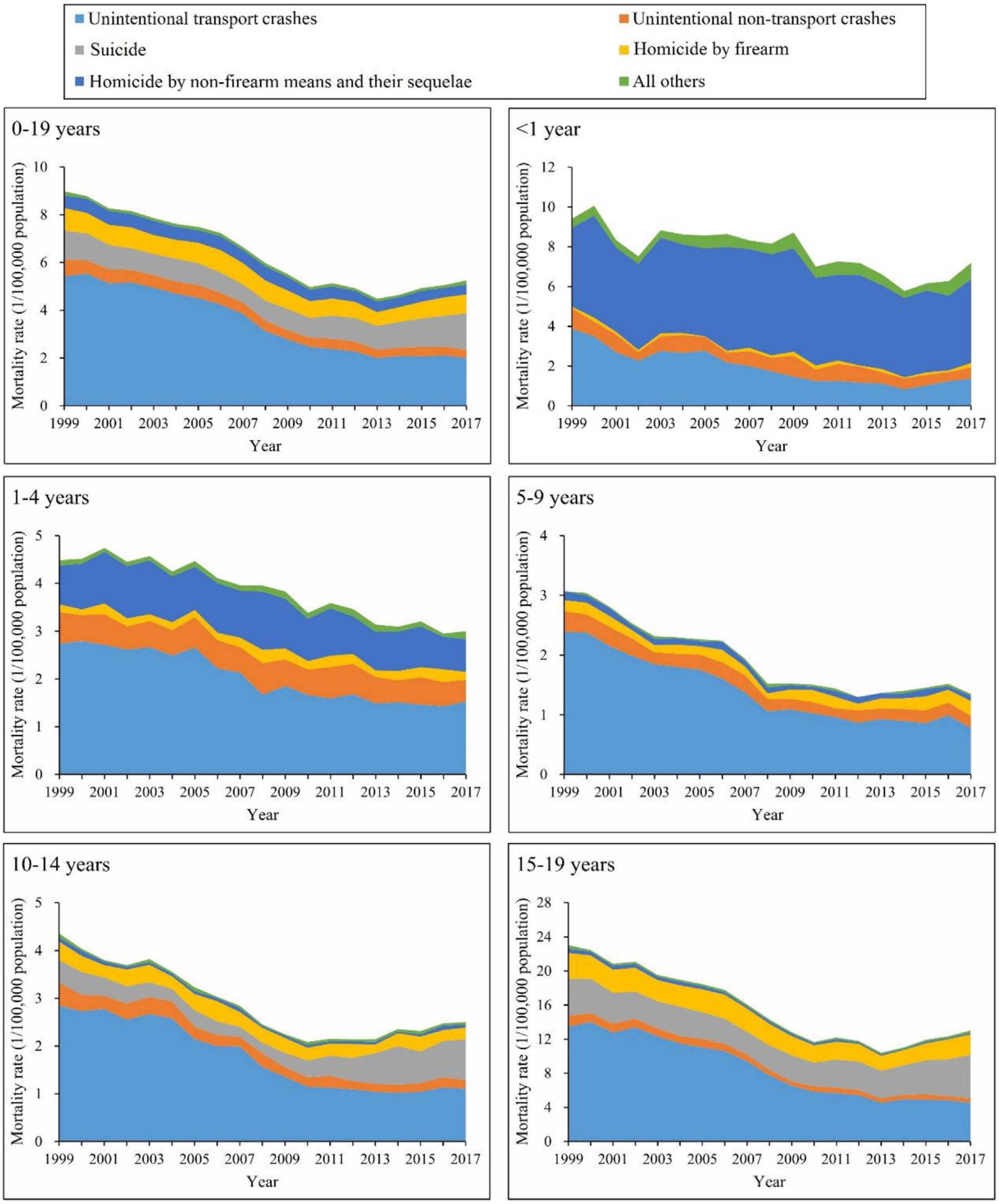

Fig. 3. Age-specific mortality (per 100,000 population) from traumatic brain injury by intent/cause in the United States, 1999–2017. Note: Because it is difficult to identify suicidal TBI among children younger than 10 years old, the suicide related TBI mortality only included deaths among people over 10 years.

from unintentional transport crashes, and then grew gradually from 2013 to 2017, primary driven by a mortality increase from suicide; (b) boys, rural children, and older children (15–19 years) were at higher risk of dying from TBI than girls, urban children, and younger children across the full study time period of 1999–2017; (c) the spectrum of leading causes of pediatric TBI mortality changed across age groups and over time from 1999 to 2017; and (d) age-adjusted TBI mortality varied greatly across U.S. states and increased significantly in seven states between 2013 and 2017. Further, the leading cause of child/adolescent TBI mortality changed from unintentional transport crashes to suicide in 14 states between 1999 and 2017.

4.2. Interpretation of findings

Consistent with previous reports from CDC (Faul et al., 2010; Taylor et al., 2017), this study detected a sharp drop in overall TBI mortality between 1999 and 2013. This is primarily due to a large mortality decrease from unintentional traffic crashes, likely the combined result of improved automobile engineering, improved road traffic safety efforts through policy and behavior change efforts, improved secondary prevention through better trauma care, and economic factors. Policy-related prevention efforts over the time period that likely contributed to the decreasing mortality trends include adoption of child restraint device laws

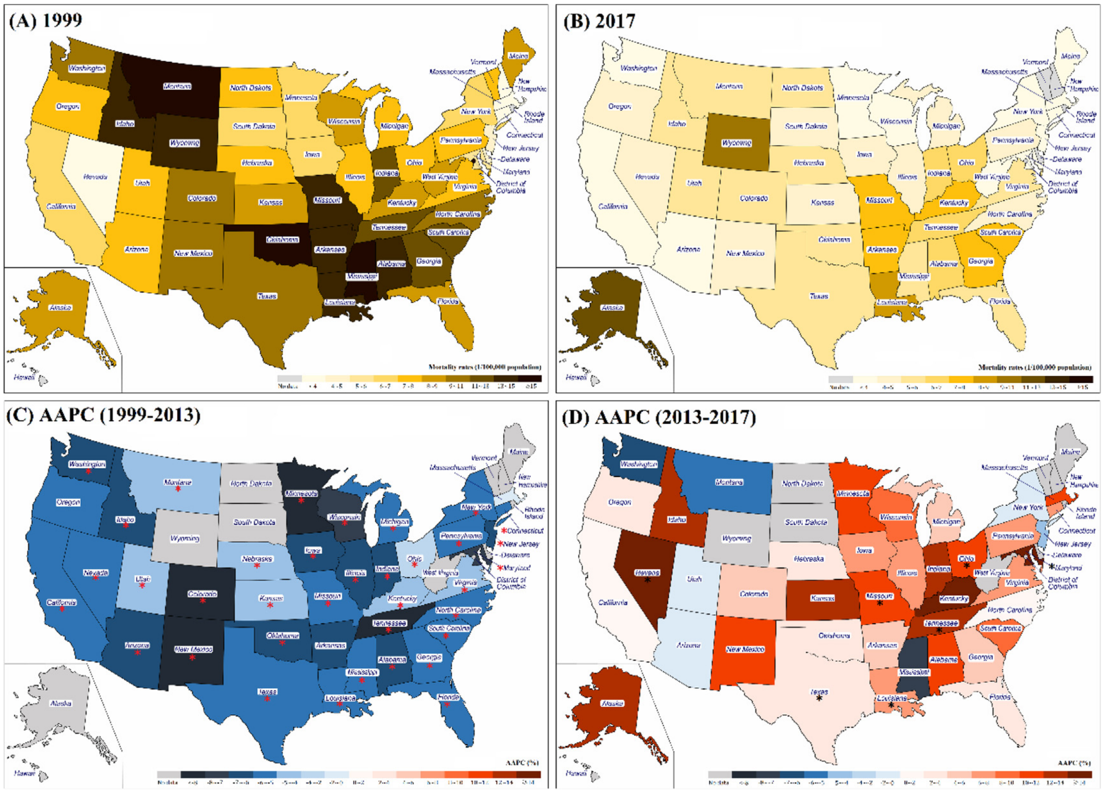

Fig. 4. Age-adjusted mortality (per 100,000 population) from traumatic brain injury by state in the United States, 1999–2017. Notes: 1. Mortality rates for traumatic brain injury were age-standardized based on the 2000 U.S. census population; 2. AAPC means average annual percent change; 3. * means AAPC was statistically significant at the significant level of $\alpha = 0.05$.

(Rice & Anderson, 2009), construction of safer roads (Bunn et al., 2003), implementation of graduated driver-licensing programs (Simons-Morton, Hartos, Leaf, & Preusser, 2006), and development of pediatric trauma care (Notrica et al., 2012). The economic recession in 2007–2009 may also have contributed to reduced crash risk by decreasing traffic volume and traffic risks (e.g., speeding) from multiple types of vehicles, including large commercial trucks (He, 2016).

From 2013 to 2017, we found the TBI mortality from unintentional transport crashes stabilized, with the exception of an increase of 64% among infants under 1 year between 2014 and 2017. These trends may reflect trade-off between successful prevention efforts and emerging risk factors such as distracted driving (U.S. Department of Transportation & National Highway Traffic Safety Administration, 2019), legalization or decriminalization of marijuana in some jurisdictions (Cunningham, Walton, & Carter, 2018), and inadequate interventions to prevent pedestrian injury (Charters, Gabbe, & Mitra, 2017).

In comparison with previous reports, we identified a gradual increase in pediatric TBI mortality since 2013, a trend that was driven primarily by rises in suicide and homicide by firearm among adolescents aged 10–19 years old. Among suicides, 96% of suicide mortality was caused by firearms (U.S. Department of Health and Human Services, 2019). We also found that suicide surpassed unintentional transport crashes to become the leading cause of TBI mortality among boys and among adolescents aged 15–19 years in 2017. These changes may reflect combined influences of media and social media on suicidality and mental illness among adolescent and pre-adolescents. Omnipresent media and social media influences offer the public increasing exposure to suicide-associated reports (Luxton, June, & Fairall, 2012). Also relevant are the comparatively high rate of access to firearms for American youth (the United States has the highest number of private guns per capita in the world, with 1.2 guns for per population in 2017 (GunPolicy.org, 2019)), and the high prevalence of mental illness among American children (13–20% of U.S. children are estimated to suffer from mental disorders (Perou et al., 2013)).

Consistent with previous reports (Taylor et al., 2017; Cheng et al., 2017), we found much higher TBI mortality rates among boys, older children, and children living in rural areas than in girls, younger children, and children living in urban and suburban areas. The discrepancies likely reflect a range of factors, including higher risk-taking behaviors among boys than girls (Reidy, Berke, Gentile, & Zeichner, 2016), lagging injury prevention efforts and inferior medical and trauma resources in rural areas (Graves et al., 2019), higher-risk activities among older children (e.g., contact sports, community violence; Centers for Disease Control and Prevention, 2011), and teen driving risks (Williams, 2009). Varying cause spectrums of TBI mortality by age group reveal differences in exposure likely related to child and adolescent development. Abusive head trauma was particularly common in young infants aged less than 2 years (Spies & Klevens, 2016). As cognitive and physical abilities develop, other injury risks emerge, including risk from sports and recreation, and through engagement in traffic as pedestrians and cyclists (Taylor et al., 2017; Cheng et al., 2017). Adolescents face increased crash risk while driving and from suicide and homicide.

Large variations across states reflect regional disparities in American health. Relevant causal factors may include road environment differences, access to quality prehospital and hospital services for trauma, especially in rural areas, and presence and enforcement of safety laws such as seat belt and child restraint use, minimum driving license age and graduated driving policies, underage drinking laws and gun laws (Reeping et al., 2019).

4.3. Policy implications

Our findings have multiple implications. They reflect notable success in reducing TBI mortality from unintentional transport crashes between 1999 and 2013, but also highlight the challenges from emerging risks, especially from suicide, to prevent child and adolescent TBI deaths. Renewed attention to TBI risks, and appropriate efforts to reduce those risks through policy-making as well as behavior change efforts and improvement of the environmental infrastructure may be needed. Policymaking attention to community violence, firearms policies, and mental health treatment could help American society build on the successes in reducing unintentional traffic crash-related pediatric TBI over the past few decades. Specific efforts could develop out of proven existing programs, such as enhancement of peer social support both in person and through social media, increased awareness among adolescents of suicide risk, and problem-solving skills to overcome such risk, readily-available effective approaches to mental health treatment (U.S. Department of Health and Human Services, 2012) and standardization of national firearm safety laws (Safavi et al., 2014).

These efforts may be challenging, as they will require substantial effort and in some cases will be politically controversial. To achieve continuing reduction in TBI rates, however, and to reduce disparities across the sexes, urban/rural populations and states, such efforts will be indispensable.

4.4. Limitations

Our study is subject to three notable limitations. First, death data are based on death certificate data that are completed by local professionals. Errors and omissions may exist, for example when deaths of intentional or unintentional intent are misclassified as being of undetermined intent (Breiding & Wiersema, 2006). CDC WONDER shows there are 1,140 injury deaths (1.14%) coded as having undetermined intent from 1999 to 2017, a figure unlikely to have a large impact on our findings. Relatedly, data were missing for a few states due to the privacy policies. Second, TBI deaths were selected by the TBI-related ICD-10 codes in any position of the mortality record in this study. There may be errors associated with selection of deaths due to the lack of specificity and sensitivity of the death certificates (Ning, Schwebel, Chu, Zhu, & Hu, 2019). Finally, we focused on fatalities, omitting nonfatal TBIs because relevant data about nonfatal TBI injuries are not freely accessible and available. Although some aspects of our results might generalize to nonfatal injuries, any generalization should be made with caution.

5. Conclusions and practical applications

Despite a substantial reduction in mortality in the United States between 1999 and 2013, pediatric TBI mortality significantly and gradually rose between 2013 and 2017. TBI mortality changes during 1999–2013 were driven primarily by mortality decreases in unintentional transport crashes; increases between 2013 and 2017 were most notably influenced by increasing suicide rates among youth aged 10–19 years. Large TBI mortality disparities existed by sex, age group, urban versus rural areas, and state. Further research and policy actions are needed to interpret recent TBI mortality changes, tailor ongoing interventions and develop new interventions, and implement evidence-based interventions and policies to reduce TBI mortality among U.S. children and adolescents aged 0–19 years.

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.

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Appendix A. Supplementary data

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