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Quality-adjusted life expectancy (QALE) loss due to smoking in the United States

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Abstract
Purpose Estimate quality-adjusted life expectancy (QALE) loss due to smoking and examine trends and state differences in smoking-related QALE loss in the U.S.
Methods Population health-related quality of life (HRQOL) scores were estimated from the Behavioral Risk Factor Surveillance System. This study constructed life tables based on U.S. mortality files and the mortality linked National Health Interview Survey and calculated QALE for smokers, non-smokers, and the total population.
Results In 2009, an 18-year-old smoker was expected to have 43.5 (SE = 0.2) more years of QALE, and a non-smoker of the same age was expected to have 54.6 (SE = 0.2) more years of QALE. Therefore, smoking contributed 11.0 (SE = 0.2) years of QALE loss for smokers and 4.1 years (37%) of this loss resulted from reductions in HRQOL alone. At the population level, smoking was associated with 1.9 fewer years of QALE for U.S. adults throughout their lifetime, starting at age 18.
Conclusions This study demonstrates an application of a recently developed QALE estimation methodology. The analyses show good precision and relatively small bias in estimating QALE—especially at the individual level. Although smokers may live longer today than before, they still have a high disease burden due to morbidities associated with poor HRQOL.

Keywords Quality of life · Life expectancy · Quality-adjusted life year · Smoking · Mortality · Morbidity

Abbreviations

BRFSS	Behavioral Risk Factor Surveillance System
NHIS	National Health Interview Survey
MEPS	Medical Expenditure Panel Survey
HRQOL	Health-related quality of life
QALE	Quality-adjusted life expectancy
QALY	Quality-adjusted life year
QWB	Quality of Well-being Scale
YPLL	Years of potential of life lost
CDC	U.S. Centers for Disease Control and Prevention

Introduction

Smoking remains the leading cause of disease and death in the United States and is a risk factor for multiple chronic diseases including cancer (lung and other sites), coronary heart disease, cardiovascular diseases (such as stroke), and respiratory problems [1, 2]. Annually in the United States, smoking causes 443,000 premature deaths among adults,

Disclaimer: The findings and conclusions in this article are those of the authors and do not necessarily represent the official position of the Centers for Disease Control and Prevention.

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contributes to approximately 5.1 million years of potential of life lost (YPLL), and costs more than $193 billion in lost productivity and healthcare expenditures [3].

While steep declines in the prevalence of smoking among adults have been observed since 1965, from 2004 to 2009, this decline in prevalence has stalled [4]. From 2003 to 2009, the rate of decline in youth smoking has also slowed so that 1 in 5 youth and 1 in 5 adults now currently smoke cigarettes. Given these current trends in smoking and its status as the leading cause of disease and death in the United States, conducting comparative analyses of burden of disease associated with smoking is important to assist in cost-effectiveness analyses of alternative health policies, intervention programs, or treatments to make further progress in reducing smoking prevalence [5, 6].

When examining the total health impact from a risk factor or a disease, such measures of burden necessarily include non-fatal morbidity such as disease, disability, or poor health–related quality of life (HRQOL), as well as life lost to premature death [5]. Thus, single indicators, such as the quality-adjusted life expectancy (QALE), are particularly useful for quantifying burden associated with behavioral risk factors, determinants of health, diseases, and injuries [7, 8]. Since HRQOL scores differ substantially across the life span, calculating life expectancy adjusted for HRQOL would provide a more complete assessment of overall health throughout the entire life span [6–8].

Kaplan et al. [9] estimated QALE loss due to smoking using the 1986–1994 National Health Interview Survey (NHIS) linked mortality file. Scores for the Quality of Well-being Scale (QWB) for participants in the NHIS were estimated based on responses to a set of measures highly correlated with the QWB. They then estimated mortality-adjusted HRQOL using polynomial regressions [9, 10]. The QALE loss was approximated by summarizing the mortality-adjusted HRQOL between ages 18 and 70. However, as the authors pointed out, this study underestimated QALE loss because it excluded losses for individuals older than 70 years. An additional weakness of the study was that state-level estimates and long-term trends could not be examined. Stewart et al. [11] used the EuroQol group's EQ-5D questions in the 2003 Medical Expenditure Panel Survey (MEPS), to obtain age-specific HRQOL scores and extrapolated future HRQOL scores as well as the prevalence of smoking to predict the long-term trends of QALE loss (from 2005 to 2020) due to smoking in the United States. Since this study relied on a single year of cross-sectional HRQOL data to predict HRQOL scores for future years, the projected estimates were less precise for years beyond 2003. Neither of these two studies was able to estimate standard errors or confidence intervals.

A recent study proposed a method to calculate U.S. State-level QALE by constructing life tables for each state and then applying population HRQOL scores, estimated from the ongoing state-based Behavioral Risk Factor Surveillance System (BRFSS), to these life tables [8]. This paper described the method to calculate QALEs and their standard errors and examined both trends (1993–2009) and between-state differences of QALE. The study demonstrated that the state estimates were reliable and that the national estimates were weakly biased.

The aim of the present study is to describe and apply a novel method to calculate QALE loss due to a specific risk factor (or a disease), smoking, using currently available data sets. Specifically, this study presents an application of a recently developed QALE methodology to examine recent U.S. trends and state-level variations in QALE loss due to smoking. Moreover, the study compares smoking-related QALE loss due to reductions in HRQOL relative to QALE loss due to shortened life expectancy.

Methods

The 1993–2009 BRFSS was used for estimating smoking status and HRQOL among respondents. The BRFSS is a state-based survey of non-institutionalized civilian adult residents from each of the fifty states and the District of Columbia [12, 13]. The BRFSS uses multistage, stratified, probabilistic sampling methods to draw representative samples of U.S. adults [13]. In addition to an unequal probability sampling weight, the BRFSS survey weight includes a post-stratification weight to correct for sampling bias due to non-response and non-coverage, which we have included in all analyses [13].

The BRFSS assesses current smoking status by asking two questions: (1) Have you smoked at least 100 cigarettes in your entire life? and (2) Do you now smoke every day, someday or not at all? Respondents who reported both ever having smoked 100 cigarettes and now smoking every day or some days were defined as current smokers [2–4]. Non-smokers included never smokers and former smokers.

The QALE uses preference-based measurements of HRQOL to capture respondents' perceived health for different health states using a summary score (also called a utility value), which is set 0 for death and 1 for perfect health [7, 14]. Thus, 1 year of life lived at a utility value of 0.8 is equal to 0.8 quality-adjusted life years [5, 15]. The BRFSS asked respondents to rank their general health from 1 (excellent) to 5 (poor) and to report numbers of their physically unhealthy days, mentally unhealthy days, and days with activity limitation during the past 30 days [16]. Because these measures are not preference based, they cannot be used to calculate QALE directly [16–18]. Thus, the present study employs a previously constructed mapping algorithm based on BRFSS respondents' age and

answers to these four questions to estimate values for a frequently used preference-based HRQOL measurement, the EQ-5D index [19–21]. This algorithm provides valid estimates of EQ-5D scores of the U.S. population from the BRFSS [8, 20], and the bias of estimated QALE from these scores has been estimated to be less than 1% of that using the actual observed EQ-5D [8].

Premature deaths attributed to smoking

The U.S. Centers for Disease Control and Prevention (CDC) compiled public use data sets that were available through 2006 that include death summary statistics (accessible at http://wonder.cdc.gov). For the years 2007–2009, these death data are not available. The U.S. Census Bureau provides annual population estimates (available till 2009, accessible at www.census.gov/popest/states/asrh/). Both sets of data are available by state, age, gender, and other basic demographics. However, since the national and state death rates were relatively stable across the time period we analyzed, we estimated these death rates for the three missing years, 2007 through 2009, using a time-series autoregressive moving average model (ARMA) from the 1993–2006 death rates [22].

The age-specific death rate (m) was obtained by dividing the number of deaths (d) by the population size (N). Because the number of deaths and the population size by smoking status were not available, death rates for current smokers (m_1) and non-smokers (m_0) were estimated using the hazard ratio (h) of dying and smoking prevalence (p) by

$$m_1 = \frac{hm}{hp + (1-p)} \quad \text{and} \quad m_0 = \frac{hm}{hp + (1-p)},$$

respectively. The hazard ratio of dying for smokers to non-smokers was estimated from the National Health Interview Survey (NHIS) Linked Mortality Files (available at http://www.cdc.gov/nchs/data_access/data_linkage/mortality/nhis_linkage.htm), using the Cox proportional hazards model. The proportion of population who smoked was estimated from the BRFSS.

QALE

Formulas to calculate QALE and their standard errors were provided by Jia, et al. [8], and details are in the "Appendix". Let A_i be the number of persons in a hypothetical population surviving to age i. Let D_i be the total life years for the age interval i and $q_i = 1 - e^{-n_i m_i}$ be the probability of dying in an n_i-year interval and assume that those who died during the interval lived an average $n_i/2$ years for ages $x < 85$, that is, $D_i = A_i(1 - n_i q_i/2)$. For the last age interval (aged 85 years and older), we assume a constant death rate (m_{85}), so that the survival time follows an exponential distribution and that $D_{85} = A_{85}/m_{85}$ [8, 15]. Suppose y_i is the mean HRQOL score, QALE for those at age x is

$$Q(x) = \frac{\sum_{i \geq x} D_i y_i}{A_x}$$

The individual QALE loss due to smoking is defined as the difference in QALE between non-smokers and smokers. Figure 1a illustrates the QALE from age 18–24 through 85+, for smokers, non-smokers, and total population. The individual QALE loss due to smoking is the difference between the non-smokers' curve and the smokers' curve. It quantifies the risk or burden of smoking at the individual level for a person who smoked (Fig. 1b). At the population level, the population QALE is defined as the difference in QALE between non-smokers and the total population. This is similar to the "population attributable risk" in epidemiology, and we will refer to this as population QALE loss.

Two factors contribute to smoking-related QALE loss: mortality and morbidity. The QALE loss that can be attributed to mortality only (i.e., shortened life expectancy) was calculated by assuming that the HRQOL scores were the same for both smokers and non-smokers, while the only difference between them was their mortality rates. Similarly, the QALE loss that can be attributed to morbidity

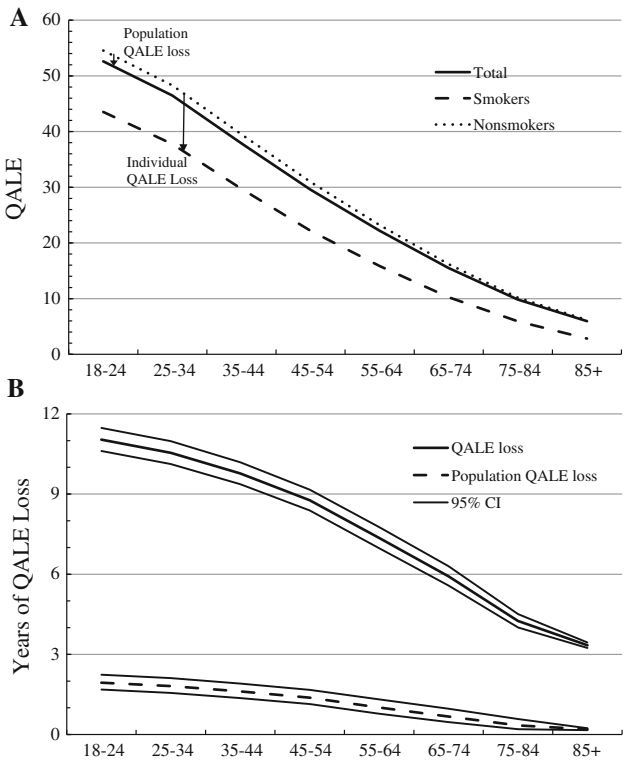

Fig. 1 QALE by age group and smoking status (**a**), and the amount of QALE loss (**b**) due to smoking among smokers (individual QALE loss) and in the entire population (population QALE loss), 2006

only (i.e., reductions in HRQOL) was calculated by assuming that the mortality rates were the same between smokers and non-smokers and that the only difference between them was their HRQOL scores.

Results

In 2009, an 18-year-old current smoker was predicted to live 53.6 more years, while a non-smoker (never or former smoker) of the same age was predicted to live 62.5 more years. This 9.0-year (SE = 0.3) difference in life expectancy between smokers and non-smokers is the loss in life expectancy due to smoking (estimates calculated but not shown). After adjustment for HRQOL scores, the QALE at 18 years for smokers, non-smokers, and the entire U.S. population were 43.5, 54.6, and 52.6 years, respectively (Fig. 1a). Therefore, smoking contributed to an average loss of 11.0 years (=54.6 − 43.5, SE = 0.2) in QALE throughout the lifetime of a smoker starting at 18 years. At the population level, smoking was expected to reduce the QALE 1.9 years over a lifetime (=54.6 − 52.6, SE = 0.14) for the U.S. population starting at 18 years. Both the individual and the population QALE loss due to smoking diminished for older age intervals (Fig. 1b). At 85 years, the QALE loss due to smoking was 3.3 years (SE = 0.05) and the population QALE loss was only 0.2 years (SE = 0.02). The steep decline in QALE loss between the ages of 18–24 and age 85+ years indicates that smoking affects smokers' health at younger ages as well as at older ages.

Figure 2a presents the trend in QALE loss due to smoking for those aged 18 years from 1993 to 2009. The following three curves occur in this figure: total loss, loss attributed to mortality, and loss attributed to morbidity. In 1993, for individual risk estimates, the QALE for smokers was approximately 9.1 years (SE = 0.1) less than non-smokers. This QALE loss increased consistently in subsequent years so that, by 2009, it had increased to 11.0 years, a 21.9% increase.

When we compared the estimates of the impact of smoking on QALE loss due to morbidity and on QALE loss due to mortality, a greater proportion of the QALE loss was due to mortality. In 2009, 7.3 years or 66.2% of the total 11.0 years of loss in QALE was due to mortality and only 4.1 years (37.4%) due to morbidity. The 0.3 years (=11.0 − 7.3 − 4.1) of overlap was probably due to the correlation between mortality rates and HRQOL scores. The QALE loss due to morbidity had increased from 2.0 years in 1993 to 4.1 years in 2009 (a 105% increase), while the QALE loss due to mortality remained relatively constant (around 7.3 years).

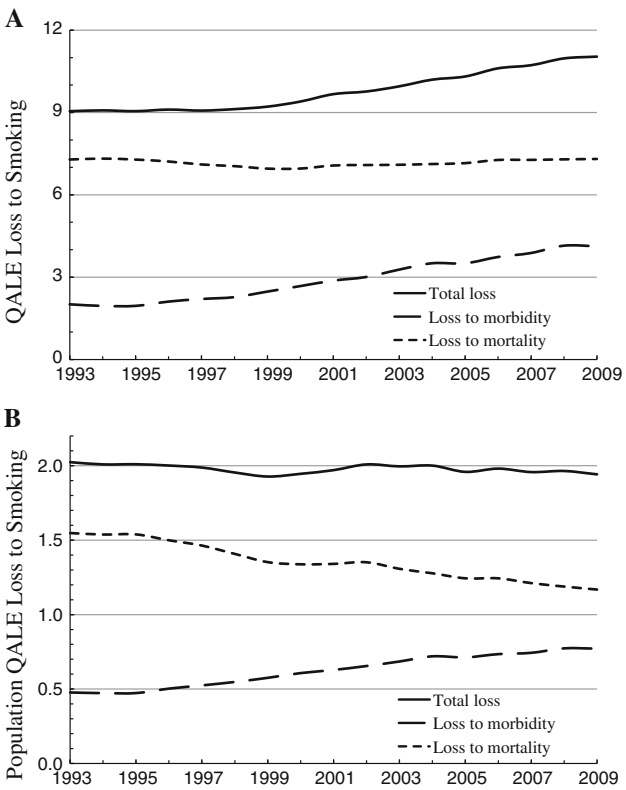

Fig. 2 Trend of QALE Loss (**a**) and population QALE loss (**b**) due to smoking at 18 years: total loss, loss to shortened life expectancy only, and loss to reductions in HRQOL only, 1993–2009

For population-level burdens (Fig. 2b), smoking contributed about 2.0 years of population QALE loss for an 18-year-old, an amount stable across the 17-year time period. However, population life expectancy loss due to smoking without adjustment for HRQOL during this time period had declined consistently from 1.9 years in 1993 to 1.4 years in 2009, a 23.8% decline (data not shown). When we examined the loss attributed to mortality and morbidity separately, of the 1.9-year loss in population QALE in 2009, 1.2 years (60.2%) were due to mortality and 0.8 years (39.7%) due to morbidity. The population QALE loss due to smoking attributed to mortality had declined from 1.5 years in 1993 to 1.2 years in 2009, a 24.5% decline. Meanwhile, the population QALE loss due to morbidity had increased from 0.48 years to 0.77 years (a 61.9% increase) during the same time period.

States varied in the amount of QALE lost to smoking (Table 1). In 2006, the most recent year when state death data are available (state-level data for other years are available upon request) states with the least loss of QALE due to smoking in the population were Utah (1.1 years), Connecticut (1.4), California (1.5), Minnesota (1.5), and Colorado (1.6); states with the greatest loss of QALE due to smoking in the population were Kentucky (2.9), West

Table 1 Losses in state-level life expectancy and quality-adjusted life expectancy due to smoking for those aged 18 years, 2006

State	LE and QALE loss				Population LE and QALE loss				Smoking (%)	
	LE loss	SE	QALE loss	SE	LE loss	SE	QALE loss	SE	%	SE (%)
Alabama	9.4	0.14	10.8	0.39	2.0	0.02	2.5	0.24	23.5	0.43
Alaska	9.3	0.45	10.0	0.77	2.0	0.08	2.3	0.42	23.6	0.59
Arizona	9.5	0.14	10.4	0.51	1.7	0.02	2.0	0.27	18.5	0.54
Arkansas	9.5	0.18	11.6	0.35	2.0	0.02	2.7	0.18	23.5	0.36
California	9.0	0.07	10.0	0.38	1.2	0.02	1.5	0.21	14.6	0.28
Colorado	8.4	0.16	9.9	0.32	1.2	0.02	1.6	0.15	18.8	0.28
Connecticut	8.4	0.18	9.6	0.35	1.1	0.02	1.4	0.16	16.6	0.30
Delaware	9.1	0.34	11.6	0.50	1.6	0.04	2.2	0.22	20.7	0.43
District of Columbia	10.4	0.43	11.6	0.54	2.2	0.06	2.4	0.22	18.5	0.41
Florida	9.9	0.08	11.6	0.29	1.8	0.01	2.3	0.15	19.9	0.30
Georgia	8.9	0.11	10.9	0.31	1.6	0.02	2.1	0.17	20.2	0.35
Hawaii	9.6	0.32	10.1	0.42	1.4	0.04	1.7	0.17	16.8	0.34
Idaho	8.5	0.28	9.9	0.41	1.3	0.03	1.7	0.19	17.7	0.33
Illinois	8.7	0.09	9.8	0.33	1.5	0.02	1.9	0.18	20.8	0.36
Indiana	8.8	0.12	10.5	0.32	1.8	0.02	2.3	0.18	25.3	0.36
Iowa	8.5	0.18	10.3	0.35	1.4	0.02	1.9	0.16	20.3	0.32
Kansas	8.7	0.20	10.4	0.31	1.3	0.02	1.8	0.13	18.7	0.26
Kentucky	8.9	0.13	11.1	0.36	2.2	0.02	2.9	0.22	27.7	0.40
Louisiana	9.7	0.15	10.6	0.35	2.0	0.02	2.3	0.21	22.5	0.33
Maine	8.5	0.27	11.1	0.44	1.3	0.03	2.0	0.21	20.2	0.35
Maryland	9.0	0.14	10.8	0.31	1.5	0.02	1.9	0.15	17.7	0.29
Massachusetts	8.3	0.13	10.9	0.30	1.2	0.01	1.8	0.14	17.4	0.25
Michigan	8.7	0.10	10.5	0.30	1.4	0.01	2.0	0.15	21.9	0.30
Minnesota	8.3	0.15	10.0	0.43	1.1	0.02	1.5	0.21	18.6	0.37
Mississippi	9.7	0.18	10.8	0.33	2.2	0.02	2.6	0.18	24.0	0.35
Missouri	8.9	0.12	11.0	0.40	1.8	0.02	2.4	0.22	24.1	0.42
Montana	8.8	0.33	11.8	0.44	1.4	0.03	2.1	0.19	19.3	0.34
Nebraska	8.4	0.24	9.5	0.36	1.3	0.03	1.6	0.16	19.7	0.32
Nevada	9.2	0.20	10.5	0.48	2.1	0.03	2.4	0.27	22.4	0.49
New Hampshire	8.2	0.27	11.2	0.42	1.3	0.03	2.0	0.18	19.5	0.31
New Jersey	8.7	0.11	9.9	0.29	1.3	0.01	1.7	0.15	17.4	0.25
New Mexico	9.6	0.24	11.5	0.40	1.9	0.03	2.4	0.19	20.4	0.33
New York	8.8	0.08	9.9	0.34	1.5	0.02	1.8	0.18	18.9	0.29
North Carolina	8.9	0.10	10.7	0.22	1.7	0.01	2.3	0.12	22.3	0.23
North Dakota	8.7	0.38	9.8	0.46	1.4	0.04	1.8	0.18	19.7	0.37
Ohio	8.7	0.09	11.1	0.38	1.6	0.02	2.3	0.21	22.8	0.41
Oklahoma	9.1	0.15	11.6	0.30	2.0	0.02	2.8	0.17	25.4	0.31
Oregon	8.5	0.17	11.1	0.36	1.2	0.02	1.8	0.16	18.0	0.31
Pennsylvania	8.9	0.09	10.5	0.28	1.7	0.01	2.2	0.15	22.1	0.30
Rhode Island	8.4	0.29	10.6	0.47	1.3	0.03	1.9	0.22	19.0	0.38
South Carolina	9.5	0.15	10.8	0.28	1.8	0.02	2.3	0.15	22.2	0.29
South Dakota	8.7	0.36	10.1	0.41	1.5	0.04	1.9	0.16	19.6	0.32
Tennessee	9.2	0.12	10.5	0.37	1.9	0.02	2.4	0.23	24.6	0.45
Texas	9.2	0.07	10.7	0.33	1.7	0.02	2.1	0.20	19.3	0.31
Utah	8.7	0.31	10.7	0.53	0.8	0.03	1.1	0.20	10.5	0.27
Vermont	8.3	0.40	10.4	0.44	1.2	0.04	1.7	0.15	18.3	0.28
Virginia	8.6	0.12	10.7	0.35	1.4	0.02	1.9	0.19	19.1	0.37

Table 1 continued

State	LE and QALE loss				Population LE and QALE loss				Smoking (%)	
	LE loss	SE	QALE loss	SE	LE loss	SE	QALE loss	SE	%	SE (%)
Washington	8.5	0.14	11.1	0.22	1.1	0.01	1.7	0.09	17.2	0.17
West Virginia	9.2	0.20	11.2	0.41	2.2	0.03	2.9	0.24	26.6	0.40
Wisconsin	8.3	0.13	9.5	0.34	1.3	0.02	1.7	0.19	20.6	0.35
Wyoming	8.9	0.43	10.2	0.46	1.6	0.05	2.0	0.18	21.2	0.33

1993–2006 contains observed mortality data, while years after 2006 contain mortality data extrapolated since 2006

Virginia (2.9), Oklahoma (2.8), Arkansas (2.7), and Mississippi (2.2). QALE loss due to smoking and life expectancy were both strongly associated with smoking prevalence rates ($r = 0.88$ and 0.81 for QALE and life expectancy, respectively).

Finally, we examined the sensitivity of using a mapping algorithm to obtain HRQOL scores from the BRFSS in the calculation of QALE. For the 2000–2003 MEPS cohorts, a nationally representative sample of 72,249 adults was asked the EQ-5D questions. We compared the QALE loss due to smoking in 2000–2003 using the estimated EQ-5D index from the HRQOL scores from the BRFSS and the observed EQ-5D from the MEPS. The mean differences between estimates using the BRFSS mapping algorithm, and the actual EQ-5D scores from the MEPS were approximately −0.25-year loss for smokers and −0.15-year loss for the entire population, resulting in underestimations of the QALE loss for smokers by 2.5% and of the population QALE loss by 7.0% (Table 2).

Discussion

The present study demonstrates use of a method to characterize trends in the total health burden of a disease or a risk factor (in this case, smoking), using a single index that incorporates both morbidity and mortality outcomes. Given the voluminous research over the past 50 years showing that cigarette smoking significantly affects both morbidity (i.e., chronic diseases and lower HRQOL scores) and mortality (i.e., premature death) throughout different stages of life [1–4], the QALE provides a novel approach to understanding the overall lifetime impact of smoking using a single value.

Unlike previous studies [9, 11], this study defined and calculated burden of disease both as an individual-level burden (among smokers) and a population-level burden (to the population as whole) separately. For the individual-level burden, the QALE loss due to smoking quantifies the degree to which risk can be prevented or reduced for current

Table 2 Sensitivity analysis—comparing estimates of quality-adjusted life expectancy loss due to smoking from the Medical Expenditure Panel Survey (MEPS) and from the Behavioral Risk Factor Surveillance System (BRFSS)

Year	Sex	QALE loss to smoking				Population QALE loss			
		MEPS	BRFSS	Bias	Bias (%)	MEPS	BRFSS	Bias	Bias (%)
2000	All	9.50	9.40	−0.10	−1.0	2.05	1.95	−0.10	−5.1
2001	All	9.74	9.67	−0.07	−0.7	2.09	1.97	−0.12	−5.6
2002	All	10.08	9.77	−0.31	−3.1	2.17	2.01	−0.17	−7.6
2003	All	10.24	9.95	−0.29	−2.8	2.16	2.00	−0.16	−7.5
2000	Male	9.91	9.85	−0.05	−0.6	2.39	2.26	−0.13	−5.4
2001	Male	10.11	9.98	−0.13	−1.3	2.41	2.26	−0.15	−6.0
2002	Male	10.49	10.08	−0.40	−3.9	2.53	2.33	−0.20	−8.0
2003	Male	10.79	10.27	−0.52	−4.8	2.53	2.31	−0.22	−8.6
2000	Female	9.19	8.73	−0.46	−5.0	1.76	1.62	−0.13	−7.5
2001	Female	9.42	9.20	−0.23	−2.4	1.80	1.68	−0.13	−7.1
2002	Female	9.69	9.33	−0.35	−3.7	1.86	1.70	−0.16	−8.7
2003	Female	9.63	9.55	−0.08	−0.8	1.82	1.69	−0.13	−7.2
	Mean	9.90	9.65	−0.25	−2.5	2.13	1.98	−0.15	−7.0
	RMSE	0.522				0.090			
	MAD	0.451				0.076			

RMSE root of mean square error; *MAD* mean absolute difference

smokers if they were not to smoke (i.e., to quit or never to have started). This measure may provide a more useful means than the population-level burden to evaluate treatment for diseases caused by smoking. From our study, we drew two conclusions. First, because two-thirds of the 11.0-year QALE loss related to smoking in 2009 could be attributed to shortened life expectancy or mortality, the main burden of smoking is still premature death. Second, because the life expectancy of smokers had increased from 51.8 to 60.8 years between 1993 and 2009 while during this period, the smoking-related QALE loss attributed to mortality remained nearly unchanged and the smoking-related QALE loss attributed to mortality had increased more than twofold, from 2.0 to 4.1 years, smokers had had declining HRQOL, which likely contributed to higher smoking-related burden.

The population QALE loss due to smoking, the burden to the entire population, measures the maximum number of QALE for the entire population that would be gained if all smokers did not smoke (quit or never to have started). This application may particularly be useful for evaluating health policies or intervention programs on smoking prevention. Our analysis showed that smoking attributed approximately 2.0 years of QALE loss for the entire U.S. population in their lifetime starting at age 18 years in recent years. Our proposed method can also be used to calculate the QALE for a population with any a given value of smoking prevalence. For example, achieving one of the Health People 2020 goals of lowering smoking prevalence to 12% for the overall United States [6] would increase QALE 0.61 years for the entire U.S. population.

Stewart et al. [11] previously calculated population QALE lost using 2003 MEPS data and found that smoking contributed to 2.2 years of population QALE lost, which was greater than our estimation of 2.0 years of population QALE lost in 2003. However, most of the 0.2-year difference appears due to the different data used in these two studies to obtain smoking prevalence: Stewart used the MEPS, and we used the BRFSS. We recalculated the population QALE loss using the smoking prevalence estimated from the MEPS, and the difference between these two studies decreased to 0.024 years. Therefore, using the BRFSS to obtain HRQOL scores underestimated the population QALE loss by 1.2%, after adjusting for the discrepancy between the BRFSS and the MEPS.

Although smoking-related QALE loss to the population was almost unchanged between 1993 and 2009, losses due to mortality had declined nearly 25% while the losses due to morbidity had increased more than 60%. This finding is consistent with CDC studies that show that both smoking attributed mortality and YPLL due to smoking among U.S. adults have decreased in recent years [2, 3], probably because life expectancy had increased and because smoking prevalence had declined in nearly all population subgroups [8, 23, 24]. Meanwhile, HRQOL in U.S. adults had also declined thus increasing QALE loss due to morbidity [25]. If the adult smoking prevalence remains constant, then the health burden of smoking to U.S. population would remain stable because the observed increasing effects of smoking on morbidity would offset the decreases related to mortality [4].

Ideally, QALE should be estimated from a longitudinal study in which HRQOL and mortality would be estimated simultaneously. But in practice, such longitudinal data are usually not available or too sparse to provide reliable estimates. Many investigators have estimated the mean HRQOL and the survival function separately from different data sets [8, 10]. The primary weakness associated with this approach is its inability to provide estimates of precision. Previous analyses have not calculated standard errors (or confidence intervals) for their QALE estimates [9, 10]. In this study, we describe a method to calculate standard errors of the estimates by assuming independence of the HRQOL and mortality rates. This independence assumption was tested in an earlier paper where the correlations between HRQOL scores and mortality rates had a very small impact (<1% relative difference) on the variance estimation of QALE [8].

The main limitation is the potential bias in the estimates. The present study relied on the unhealthy days questions in the BRFSS to estimate preference-based HRQOL scores. The only other large and population data that included preference-based HRQOL questions were available from MEPS [18]. Therefore, estimates of smoking-related QALE loss would likely be underestimated [8, 20, 26, 27] in our study. Our estimates of smoking-related QALE loss in the population may also be underestimated because they do not account for possible mortality of other persons due to second-hand smoke or fire injury. In fact, our sensitivity analysis comparing BRFSS and MEPS shows that these underestimations were about 2.5% for QALE loss to smoking and 7% for population QALE loss. We consider such biases acceptable given the lack of other preference-based HRQOL data for such estimation. Also, part of the discrepancy between the MEPS and the BRFSS was due to sampling differences between these surveys. The actual bias can be as small as 1.2% for population QALE loss. Second, the number of BRFSS respondents and the number of deaths might be too small to provide reliable estimates for all states. Because some questions were not asked in all states every year, we had to rely on moving averages to obtain estimates for these years and states. Nonetheless, standard errors of almost all (93.5%) of these state-level estimates were less than 0.5 year, and all of the relative standard errors were <30%.

Smoking status was based on self-report and was not validated by biochemical tests. However, using the levels of serum cotinine (a breakdown product of nicotine), similar prevalence estimates were observed as those obtained from self-reports [28]. Finally, for the more recent

years of BRFSS data collection, adults without telephone service or with wireless-only service who more often currently smoke than adults with landline telephones were excluded so that the overall adult smoking prevalence estimates in this study were likely underestimated [29].

In summary, this study presents a method to estimate lifetime burdens due to smoking by calculating the QALE, a single measure that encompasses smoking-related morbidity and mortality to smokers only and for the entire population. One of the primary advantages of this method is its ability to use currently available data to estimate trends in the burden of smoking for U.S. states as far back as 1993. While the method is novel, it has the potential to provide estimates of geographic variations between states as well as some large substate areas. Furthermore, demographic subgroups can be examined such as by sex and race (data stratified by sex are available upon request). The method developed here may also be applied to randomized controlled trials to compare outcomes between treatment and control groups for the cost-effective analysis of alternative treatments [5, 14]. The potential utility of the QALE outlined in this study provides a means to obtain burden of smoking estimates essential for setting targets to reduce health risks from cigarette smoking, eliminating health disparities, and assisting policy makers with decision making [6].

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Appendix

The QALE at age x is calculated by summarizing QALYs throughout remaining expected life starting at age x over the percent of population surviving to age x [7, 8]:

$$Q(x) = \frac{\int_{\geq x} S(t)y(t)\mathrm{d}t}{S(x)},$$

where $y(t)$ are HRQOL scores at age t and $S(t)$ is the survival function. Formulas to calculate QALE and their standard errors were provided by Jia et al. [8]. QALE for those at age x is:

$$Q_x = \frac{\sum_{i\geq x} D_i y_i}{A_x}$$

The variance of this QALE estimate is:

$$\mathrm{VAR}(Q_x) = \frac{\sum_{i=x}^{84}\left[A_i^2\left(\frac{n_i y_i}{2} + \mathrm{Q}_{i+1}\right)^2\mathrm{VAR}(q_i) + A_i^2\left(1-\frac{q_i}{2}\right)\mathrm{VAR}(y_i)\right]}{A_x^2} + \frac{\mathrm{VAR}(L_{85})y_{85}^2 + D_{85}^2\mathrm{VAR}(y_{85}) + \mathrm{VAR}(L_{85})\mathrm{VAR}(y_{85})}{A_x^2}$$

where $\mathrm{VAR}(q) = \frac{q^2(1-q)}{d}$ for age less than 85 and $\mathrm{VAR}(L_{85}) = \frac{\left(e^{-\sum_{k<85} n_k m_k}\right)^2}{d_{85}m_{85}^2}A_{18-24}^2$.

QALE loss was the difference in QALE between two groups: $\Delta_x = Q_x^0 - Q_x^1$. Here, Q_x^0 is QALE for non-smokers and Q_x^1 is QALE for smokers (for individual QALE loss) or for total population (for population QALE loss). The variance of QALE loss is equal to $\mathrm{Var}(\Delta_x) = \mathrm{Var}(Q_x^0) + \mathrm{Var}(Q_x^1) - 2\mathrm{COV}(Q_x^0, Q_x^1)$. The covariance term is approximated by

$$\mathrm{COV}\left(Q_x^0, Q_x^1\right) \approx \frac{1}{A_x^0 A_x^1}\left[\sum_{i<85}\frac{\partial Q^0}{\partial q_0}\frac{\partial Q^1}{\partial q_1}\mathrm{COV}(q_0,q_1) + \sum_{i<85}\frac{\partial Q^0}{\partial y_0}\frac{\partial Q^1}{\partial y_1}\mathrm{COV}(y_0,y_1) + \sqrt{\mathrm{VAR}\left(L_{85}^0\right)\mathrm{VAR}\left(L_{85}^1\right)}\rho_{m_0,m_1}y_0y_1 + D_{85}^0D_{85}^1\rho_{y_0y_1}SE_{y_0}SE_{y_1}\right],$$

where $\frac{\partial Q^0}{\partial q^0} = A_i\left(\frac{ny}{2} + \mathrm{Q}_{i+1}\right)$ and $\frac{\partial Q^0}{\partial y_0} = A_i\left(1-\frac{q_i}{2}\right)$ for i < 85.

Since the number of deaths is estimated from the proportion at risk and the hazard ratio, additional variation from the unreliability of using the estimated proportion (var(p)) and hazard ratio (var(h)) should be included in the variance estimation for q, the probability of dying:

$$\mathrm{var}(q) \approx \frac{(q^2)(1-q)}{d} + n^2(1-q)^2 \times \left[\frac{h^2m^2(h-1)^2}{(hp+1-p)^4}\mathrm{var}(p) + \frac{m^2(1-p)^2}{(hp+1-p)^4}\mathrm{var}(h) + \left(\frac{h}{hp+1-p}\right)^2\mathrm{var}(m)\right]$$

The values of var(p) and var(h) are derived from methods of moments estimation (either using designed based on direct estimates or using model-based estimates). For the years 2007–2009, the death data were estimated from a time-series autoregressive moving average model (ARMA) from the 1993–2006 death rates [8, 22]. The death rate at year t, m_t, is specified as ARMA(1,1) or $m_t - \mu = \rho(m_{t-1} - \mu) + e_t - \beta e_{t-1}$. The predicted death rates for these 3 years therefore should include additional uncertainty in their estimates, and the variance, var(m), from the ARMA model estimates was used to account for this.

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