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Health Estimates Using Survey Raked-Weighting Techniques in an Australian Population Health Surveillance System

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A challenge for population health surveillance systems using telephone methodologies is to maintain representative estimates as response rates decrease. Raked weighting, rather than conventional poststratification methodologies, has been developed to improve representativeness of estimates produced from telephone-based surveillance systems by incorporating a wider range of sociodemographic variables using an iterative proportional fitting process. This study examines this alternative weighting methodology with the monthly South Australian population health surveillance system report of randomly selected people of all ages in 2013 ($n = 7{,}193$) using computer-assisted telephone interviewing. Poststratification weighting used age groups, sex, and area of residence. Raked weights included an additional 6 variables: dwelling status, number of people in household, country of birth, marital status, educational level, and highest employment status. Most prevalence estimates (e.g., diabetes and asthma) did not change when raked weights were applied. Estimates that changed by at least 2 percentage points (e.g., tobacco smoking and mental health conditions) were associated with socioeconomic circumstances, such as dwelling status, which were included in the raked-weighting methodology. Raking methodology has overcome, to some extent, nonresponse bias associated with the sampling methodology by incorporating lower socioeconomic groups and those who are routinely not participating in population surveys into the weighting formula.

health estimates; nonresponse bias; poststratification weighting; public health surveillance; raked weights; telephone surveys

Abbreviations: AHS, Australian Health Survey; BRFSS, Behavioral Risk Factor Surveillance System; HOS, Health Omnibus Survey; SAMSS, South Australian Monitoring and Surveillance System.

Chronic disease and behavioral risk factor surveillance systems have been established in many countries, including Australia (1–6), as a response to the rising prevalence of chronic diseases and the contributing preventable lifestyle factors (7, 8). To be effective and valuable, the system must be quick, relatively inexpensive, flexible, representative, population based, continuous, and with independent samples drawn at each time period (9, 10). Because of these requirements, many systems use telephone surveys based on computer-assisted telephone-interviewing technology (1–3, 5, 11–16).

In the last decade, telephone surveys have undergone many changes because of nonresponse and noncoverage (15, 17, 18), with a resultant potential loss in the precision of survey estimates. *Nonresponse* can be defined as "the failure to obtain a valid response from a sampled unit" (18, p. 329) and is usually measured by response rates (19). Response rates have been declining in population surveys of all modes: face-to-face, mail, Internet, and telephone surveys (20). Reasons for falling response rates are the increasing proportion of people not willing to participate in surveys of any kind and the inability to establish contact with potential participants (18, 20). *Noncoverage* can be defined as "the proportion of the target population not covered by the sampling frame" (21, p. 55). The majority of telephone surveys in Australia rely

on sampling frames that consist mainly of landline telephone numbers (2, 3, 14, 22–24). Over the past decade, nationally and internationally, society has moved away from the traditional landline telephones to flexible communications, such as the mobile telephone (15, 17, 23, 25–29). This transition is associated with an increase in mobile-only households. In Australia, this has implications for telephone surveys because of the difficultly of obtaining a sample of mobile telephone numbers with a geographical location, such as postcode or state. Australian data from 2011 have estimated that 22% of households are mobile only, which is an increase of over 75% since 2006 (5.2%) (25). More importantly, this group is not uniformly distributed in the population (23, 30). These mobile-only households result in specific groups being excluded from the traditional sampling frames used for telephone surveys. These include younger people and people who are unemployed, rent their housing, and reside in low socioeconomic areas (15, 17, 23–29, 31, 32). This is compounded in most countries by the difficulty in obtaining a cost-effective and efficient sampling frame (23, 26) and has led to the declining representativeness of surveillance systems based on telephone survey sampling methodology (16, 17). Recent debates have questioned the value of representativeness in epidemiologic study designs, particularly those focused on examining the causal effect of exposures or interventions on outcomes (33). Descriptive studies, where the aim is to estimate the occurrence of a disease or risk factor in a given population, however, are the case for which representativeness is universally supported (34–37).

Various statistical methods have been developed to address and improve the representativeness of the estimates produced from telephone-based surveillance systems due to nonresponse. A common statistical approach is to weight the survey data on the basis of the sociodemographic variables that are under- or overrepresented in the sample, such that the proportion of the cases in the sample is adjusted to the population proportion as in the census (15). Weighting approaches can be seen as a form of imputation, where the weight of the nonresponders is distributed to other similar respondents (38). These imputation methods are model based and are described in detail elsewhere (39). Weighting is a technique for adjusting the unit record survey such that the data structure is made similar to the population structure in terms of sociodemographic indicators, such as, age and sex, so that inferences can be made. Weighting by the appropriate variables allows point and parameter estimates generated from survey data (e.g., means, proportions, and regression coefficients) to be unbiased population estimates, and it involves statistically increasing or decreasing the numbers of cases (17, 21). This means that a weighting value is calculated for each individual who participates in a survey, and that weighting value indicates how much the individual's response will count in a statistical procedure. Weighting values are often represented as a fraction, they have a mean value of 1.0, and the sum of the weighting values usually equals the sample size, is always positive, and is non-0 (e.g., 1.35, 0.75). To illustrate, a participant with a weighting value of 2.0 means that his/her response is counted 2 times compared with a participant with a weighting value of 0.5, which means that his/her response is half a count. Using diabetes prevalence as an example, researchers have found that general population surveys in Australia usually have a higher proportion of older people than younger people participating. Unweighted data indicate that 12.0% of the sample has diabetes, but this estimate is an overestimation because we have a higher proportion of older people. With weighted data, older respondents have weighting values less than 1.0 and younger respondents have weighting values greater than 1.0; this results in a diabetes prevalence of 7.7% that is more reflective of the population.

The weights are developed in a series of stages. One is to calculate the base weight (40), which is to take into account the complex sampling design and to adjust the data according to the different selection probabilities and the complex sampling design. For example, only 1 eligible person is selected at random within a household to participate (21). The other part is cell weighting or poststratification adjustments (the focus of this paper) that modify the survey data by particular characteristics so that the proportion of cases in the sample is adjusted to the population proportion, such as census data. The standard *poststratification* weighting (or cell weighting) method adjusts the sample data by creating a cross-classification of categorical variables (e.g., age groups × sex × area of residence × marital status × income) and matches the proportions to population data. However, this method has limitations as each addition of a variable in the cross-tabulations can result in smaller or empty cell sizes that can result in unstable weights. Therefore, only a few variables are usually included, typically, age group, sex, and area of residence.

The US Behavioral Risk Factor Surveillance System (BRFSS) has implemented a statistical technique called *raked weights* or *raking* to address the problem with the *poststratification* weighting method (12, 41). Raking adjusts the sample data 1 variable at a time by using an iterative proportional fitting process (42, 43). Changes in some BRFSS health estimates, including prevalence of current smokers, no physical activity, or perceived health as fair or poor, have resulted when raked weights were applied (12, 42, 44). However, they have also found that the prevalence of other health conditions, such as diabetes and coronary heart disease, remained the same.

The raking iterative process can be explained by using the following example with 2 variables: age (i.e., 7 age group categories) and sex (2 categories). Starting with age groups, each case is multiplied by the ratio of the population total to the weighted sample total for each age group category. This will result in the age group category totals of the adjusted weighted data agreeing with the population totals. However, the weighted category totals for the sex variable do not agree with its corresponding population category totals. The next step is to take the sex variable and multiply each case by the ratio of the population total to the weighted sample total for each sex group category. Now the new calculated weighted category totals for sex will agree with the population totals for sex. However, the weighted category totals for the age group variable do not agree with its corresponding population category totals, and the calculation is repeated, until the weighted category totals for both age groups and sex agree with the corresponding population category totals.

The challenge for chronic disease and behavioral risk factor surveillance systems utilizing the telephone in Australia and similar countries is to ensure that the methodology is effective

and efficient in obtaining and providing representative and reliable population data. This raking weighting method has not been applied in Australia but could potentially reduce bias in the estimates from Australian chronic disease and risk factor surveillance systems. It is not known if major differences across weighting methods found in the BRFSS would apply in Australia (with higher responses rates and different ethnicity and socioeconomic distributions). The main objective of this paper is to apply the raking methodology to data from an Australian population health surveillance system and to examine the impact on the estimates produced by use of traditional (cell weighting) and raked weights.

METHODS

Survey design and sample selection

Data for this study were collected by using the South Australian Monitoring and Surveillance System (SAMSS) in 2013. SAMSS is a telephone-monitoring system designed to monitor, over time, the health conditions, risk factors, and other health service issues in South Australia (1). Approximately 600 randomly selected interviews were conducted for all ages each month. Households in South Australia with a telephone connected and listed in the telephone directory were eligible. A letter introducing the survey was sent to the selected household. Within each household, the person with the most recent birthday was chosen for interview. There were no replacements for nonrespondents. Up to 10 callbacks were made to the household to interview the selected person. Interviews were conducted by trained health interviewers via a computer-assisted telephone-interviewing system. Ethical approvals were obtained from the human research ethics committees of The University of Adelaide and the South Australia Department of Health. Participants gave verbal informed consent to participate in the telephone interview. A total of 7,193 interviews were conducted in 2013 with a 61.7% response rate.

Sociodemographic variables used for raked-weighting methodology

The population source was the 5-yearly Australian Bureau of Statistics 2011 Census, using TableBuilder Pro (45), which allowed some flexibility in constructing summary data to match with SAMSS demographic questions. Nine sociodemographic variables to be incorporated into the raked-weight methodology were ascertained as suitable and are shown in Table 1. Sociodemographic variables were considered if they had a strong association with various chronic disease and behavioral risk factors or were strongly related to nonresponse or noncoverage. Sociodemographic variables with categories having less than 5% in the sample were not considered, such as Aboriginal/Torres Strait Islander status. Categories were collapsed, or variables were excluded if there was a high proportion of missing data or difficulties in harmonizing the categories or variables between SAMSS and the census because of wording differences.

Sociodemographic variables used for poststratification weighting

The variables used for poststratification weighting were age groups, sex, and area of residence, as described for raked weights (Table 1).

Outcome variables

For respondents aged 16 years or more, self-reported health conditions included overall health status, diabetes, cardiovascular disease (heart attack, angina, heart disease, and/or stroke), arthritis, current asthma (46), chronic obstructive pulmonary disease, and osteoporosis. Having a chronic condition included diabetes, current asthma, cardiovascular disease, arthritis, or osteoporosis. Psychological distress used 10 questions from the Kessler 10 screening scale (47) scored to a single scaled

Table 1. Variables Used in Weighting (Poststratification and Raking)

Variable	Categories	Poststratification Weights	Raked Weights
Sex	Male, female	Yes	Yes
Age groups	0–9, 10–15, 16–34, 35–44, 45–54, 55–64, 65–74, ≥75 years	Yes	Yes
Area of residence	Metropolitan Adelaide, rural or remote areas	Yes	Yes
Country of birth	Australia, United Kingdom, Europe, other	No	Yes
Dwelling status	Renting, other (owned or being purchased, other)	No	Yes
Marital status (16 years or more)	Married or living with partner, other (widowed, separated, divorced, never married)	No	Yes
Educational level (16 years or more)	Bachelor's degree or higher, other (none to some high school, trade, certificate, diploma)	No	Yes
Employment status (16 years or more)	Full-time employed, part-time employed, unemployed, other (home duties, student, retired, unable to work)	No	Yes
No. of people in the household (including children)	1, 2, 3, 4 or more	No	Yes

Table 2. Demographic Profile of the South Australian 2011 Census and Estimates for All Age Groups From the 2013 South Australian Monitoring and Surveillance System Using Unweighted Data and Data With Poststratified Weights and Fully Raked Weights

Sociodemographic Variable	2011 Census (n = 1.60 million), %	2013 SAMSS (n = 7,193)					
		Unweighted		Poststratification Weights[a]		Fully Raked Weights[b]	
		%	% Difference[c]	%	% Difference[c]	%	% Difference[c]
Age groups, years							
0–9	11.9	7.2	−4.70	11.9	0.00	11.9	0.00
10–15	7.4	5.7	−1.70	7.4	0.00	7.4	0.00
16–34	24.4	10.5	−13.90	24.4	0.00	24.4	0.00
35–44	13.5	5.9	−7.70	13.5	0.00	13.6	0.00
45–54	14.1	12.2	−1.89	14.1	0.00	14.1	0.00
55–64	12.5	20.1	7.65	12.5	0.00	12.5	0.00
65–74	8.3	21.4	13.05	8.3	0.00	8.3	0.00
≥75	7.8	17.0	9.21	7.8	0.00	7.8	0.00
Sex							
Male	49.3	42.1	−7.17	49.3	0.00	49.3	0.00
Female	50.7	57.9	7.17	50.7	0.00	50.7	0.00
Area of residence							
Metropolitan Adelaide	71.6	63.7	−7.92	71.6	0.00	71.6	0.00
Rural or remote areas	28.4	36.3	7.92	28.4	0.00	28.4	0.00
Dwelling status							
Owned or being purchased, other	72.2	86.5	14.24	85.4	13.16	72.2	0.01
Rent	27.8	13.5	−14.24	14.6	−13.16	27.8	−0.01
Country of birth							
Australia	76.9	78.7	1.79	82.9	5.99	76.9	0.00
United Kingdom	8.3	11.5	3.21	7.5	−0.76	8.3	0.00
Europe	5.4	5.6	0.22	4.1	−1.26	5.4	0.00
Other	9.5	4.2	−5.22	5.5	−3.96	9.5	0.00

Table continues

item, where respondents with high scores of 22–50 were categorized as having psychological distress (48). Having a current mental health condition meant a diagnosis of and/or treatment for anxiety, depression, a stress-related problem, or another mental health problem. Suicidal ideation used 4 items from the 28-item General Health Questionnaire (49) that produced a score ranging from 0 to 4, where a score of 1 or more indicated suicidal ideation (50).

For respondents aged 16 years or more, self-reported health-related risk factors included current or receiving treatment for high blood pressure and cholesterol, sufficient physical activity (51), smoking status, lifetime risk of harm to health from alcohol consumption (52), and overweight or obese status (53) (as determined by a body mass index (self-reported weight in kilograms divided by height in meters squared) ≥25.0). Recommended amounts of fruit and vegetables for people aged 18 years or more were defined as having at least 5 daily servings of vegetables and 2 daily servings of fruit (54). Recommended daily servings of fruit (1–2 servings) and vegetables (2.5–5.5 servings) for children aged 2–17 years varied according to age (54).

Food insecurity was defined as households running out of food or could not afford to buy more in the last 12 months. Respondents were asked the number of times they had takeaway (carryout) food per week. The family money situation was divided into 2 groups: unable to save (spending more money than getting, having just enough to get through to the next pay, having some money left over each week but just spending it) and able to save (can save a bit occasionally or a lot).

Survey weight adjustment methods

Raking is an iterative process, and usually 1 variable at a time is applied to the proportional adjustment of the weights. The data are gradually adjusted to fit to specific characteristics so the survey variables (or survey margin totals) match with population variables (or control totals) such as census data (42, 43, 55). The iterative process is finalized when the differences between all the categories' proportions from the census data and raked weights from the survey data margin are convergent within an acceptable predefined tolerance

Table 2. Continued

Sociodemographic Variable	2011 Census (n = 1.60 million), %	2013 SAMSS (n = 7,193)					
		Unweighted		Poststratification Weights[a]		Fully Raked Weights[b]	
		%	% Difference[c]	%	% Difference[c]	%	% Difference[c]
Marital status							
Married/living with partner	43.2	49.8	6.62	47.7	4.52	43.1	−0.04
Other	37.6	37.3	−0.26	33.0	−4.56	37.6	0.00
Under 16 years	19.2	12.9	−6.36	19.3	0.03	19.3	0.04
Educational level							
None to some high school, trade, certificate, diploma	69.8	70.8	1.01	63.9	−5.90	69.8	−0.03
Degree or higher	11.0	16.3	5.35	16.8	5.86	11.0	−0.01
Under 16 years	19.2	12.9	−6.36	19.3	0.03	19.3	0.04
Employment status							
Full-time employed	31.2	21.4	−9.74	28.1	−3.04	31.2	0.01
Part-time employed	17.1	14.4	−2.73	16.1	−0.96	17.1	0.01
Unemployed	2.9	1.5	−1.39	1.9	−0.96	2.8	−0.09
Economically inactive (home duties, student, retired, unable to work because of illness)	29.6	49.9	20.22	34.6	4.93	29.7	0.02
Under 16 years	19.2	12.9	−6.36	19.3	0.03	19.3	0.04
No. of people in the household (including children)							
1	26.4	25.9	−0.49	9.4	−17.07	26.4	−0.04
2	34.7	41.1	6.43	27.7	−6.97	34.7	−0.01
3	15.5	12.2	−3.31	18.0	2.50	15.6	0.02
≥4	23.4	20.7	−2.62	44.9	21.55	23.4	0.03

Abbeviation: SAMSS, South Australian Monitoring and Surveillance System.

[a] Three variables included in poststratification weights (age, sex, area of residence).

[b] All 9 variables included in raked weights (age, sex, area of residence, dwelling status, country of birth, marital status, educational level, employment status, and number of people in household).

[c] Percentage differences are between the 2011 Census and SAMSS.

limit of 0.025 (43, 56). For example, the raked weighted proportion of males from the survey data (49.3%) is the same as the census proportion of males (49.3%). Alternatively, the process is terminated once a predefined set number of iterations has been reached, for example, 60 (43). As recommended by Izrael et al. (43) and Battaglia et al. (55, 57), raked weights that had extremely high or low weight values in our sample were trimmed to reduce their impact on the variance of the estimates by recoding weights larger or smaller than the median weight plus 6 times the interquartile range of the weight to these limits. A raking program, using SPSS version 20.0 syntax code (IBM SPSS Statistics for Windows software; IBM Corp., Armonk, New York), to calculate the raked weights was developed, and the base design weight (the number of people living in the household and the number of telephone listings in the telephone directory) was included in the calculation. User-written programs on raked weights have been developed and are available for general use in SPSS (*SPSS_RAKE*) and Stata (*ipfraking*) statistical software (StataCorp LP, College Station, Texas).

Poststratification weighting of SAMSS used area of residence (metropolitan Adelaide, rural or remote areas), 10-year age groups, sex, and probability of selection in the household to the most recent estimated residential population or census data. Probability of selection in the household is based on the number of people living in the household and the number of telephone listings in the telephone directory.

A detailed explanation of poststratification and raked weights is in the Appendix.

Statistical analyses

Data analysis was conducted by using SPSS version 20.0. Prevalence estimates were presented for self-reported fair or poor health, diabetes, current smokers, and current high blood pressure by using poststratification weights and raked weights. These 4 variables were used to demonstrate the impact on the estimates by use of different sociodemographic variables, besides age, sex, and area of residence, in raked weights. For other selected health indicators, the differences between

Table 3. Effect of Including Different Sociodemographic Variables in the Raked Weights on Health Prevalence Estimates for Persons Aged 16 Years or More, South Australian Monitoring and Surveillance System, 2013

Variables Used in Poststratified and Raked Weights	Fair/Poor Overall Health		Diabetes		Current Smokers		Current High Blood Pressure	
	Prevalence, %[a]	95% CI	Prevalence, %	95% CI	Prevalence, %	95% CI	Prevalence, %	95% CI
Unweighted	20.3	19.3, 21.3	12.0	11.3, 12.9	11.5	10.8, 12.4	34.9	33.7, 36.0
Poststratification weight	15.3	14.4, 16.3	7.7	7.1, 8.4	12.8	11.9, 13.6	20.7	19.6, 21.7
Raked weights calculated by using								
Age, sex, area of residence	15.5	14.5, 16.4	7.6	7.0, 8.3	12.7	11.9, 13.6	20.7	19.6, 21.7
Age, sex, area of residence, dwelling status	16.5	15.6, 17.5	8.1	7.4, 8.8	14.4	13.5, 15.3	21.0	20.0, 22.1
Age, sex, area of residence, country of birth	15.4	14.4, 16.3	7.7	7.0, 8.4	12.5	11.7, 13.4	20.6	19.6, 21.7
Age, sex, area of residence, marital status	15.9	14.9, 16.8	7.7	7.1, 8.5	13.3	12.4, 14.2	20.8	19.8, 21.9
Age, sex, area of residence, educational attainment	15.8	14.8, 16.7	7.8	7.2, 8.6	13.6	12.7, 14.5	21.2	20.1, 22.2
Age, sex, area of residence, employment status	14.8	13.9, 15.8	7.5	6.8, 8.2	12.9	12.1, 13.8	20.3	19.3, 21.3
Age, sex, area of residence, no. of people in household	16.7	15.7, 17.6	8.2	7.5, 8.9	14.7	13.8, 15.6	21.2	20.2, 22.3
Age, sex, area of residence, dwelling status, country of birth	16.4	15.4, 17.3	8.1	7.4, 8.8	14.2	13.3, 15.1	21.1	20.1, 22.2
Age, sex, area of residence, dwelling status, country of birth, marital status	16.7	15.7, 17.6	8.2	7.5, 8.9	14.7	13.8, 15.6	21.2	20.2, 22.3
Age, sex, area of residence, dwelling status, country of birth, marital status, educational attainment	17.1	16.2, 18.1	8.3	7.6, 9.0	15.5	14.6, 16.5	21.8	20.7, 22.9
Age, sex, area of residence, dwelling status, country of birth, marital status, educational attainment, employment status	16.0	15.1, 17.0	8.0	7.3, 8.7	15.6	14.7, 16.6	21.3	20.2, 22.3
Fully raked (9 variables): age, sex, area of residence, dwelling status, country of birth, marital status, educational level, employment status, no. of people in household	18.1	17.1, 19.1	8.4	7.8, 9.2	16.3	15.4, 17.3	21.6	20.6, 22.7

Abbreviation: CI, confidence interval.

[a] All prevalence values are estimates.

poststratification weights and the fully raked weights were calculated. The raked-weight methodology was assessed by comparing the raked estimates with 2 external data sources: the 2013 Health Omnibus Survey (HOS) (58) and the 2011–2012 Australian Health Survey (59) (AHS) where the questions were the same or very similar. HOS is an annual face-to-face household survey of South Australians with a 57.6% response rate, and the AHS is a face-to-face survey of all

Table 4. Prevalence Estimates, Differences, and Percentage Change of Various Health Conditions, Behavioral Health Risk Factors, and Other Health-Related Issues Between Poststratified Weights and Raked Weights, South Australian Monitoring and Surveillance System, 2013

Variable	Poststratification Weights		Fully Raked Weights		Differences, %	Percentage Change
	Prevalence, %[a]	95% CI	Prevalence, %[a]	95% CI		
Health conditions						
Current asthma (children)	13.8	12.0, 15.8	14.1	12.3, 16.2	0.3	2.2
At least 1 chronic condition	38.3	37.1, 39.6	40.3	39.0, 41.6	2.0	5.2
Cardiovascular disease	7.4	6.8, 8.1	7.8	7.2, 8.6	0.4	5.4
Current asthma (adults)	13.2	12.3, 14.1	14.0	13.1, 14.9	0.8	6.1
Osteoporosis	4.4	3.9, 5.0	4.7	4.2, 5.3	0.3	6.8
Chronic obstructive pulmonary disease	3.4	3.0, 3.9	3.7	3.3, 4.3	0.3	8.8
Diabetes	7.7	7.1, 8.4	8.4	7.8, 9.2	0.7	9.1
Arthritis	20.6	19.5, 21.6	23.0	22.0, 24.1	2.4	11.7
Self-reported fair or poor	15.3	14.4, 16.3	18.1	17.1, 19.1	2.8	18.3
Current diagnosed mental health condition	16.6	15.7, 17.6	20.0	19.0, 21.1	3.4	20.5
Psychological distress (Kessler 10)	8.8	8.1, 9.6	11.3	10.5, 12.1	2.5	28.4
Suicidal ideation	3.6	3.1, 4.1	5.1	4.6, 5.7	1.5	41.7
Behavioral health risk factors						
Sufficient servings of fruit per day (children)	67.1	64.8, 69.3	67.8	65.3, 70.2	0.7	1.0
Lifetime risk of harm due to alcohol consumption	33.1	31.9, 34.3	32.7	31.5, 33.9	−0.4	−1.2
Sufficient physical activity	42.7	41.4, 44.0	40.9	39.7, 42.2	−1.8	−4.2
Overweight/obesity	59.0	57.6, 60.3	61.5	60.2, 62.8	2.5	4.2
Sufficient servings of fruit per day (adults)	44.3	43.0, 45.6	42.4	41.1, 43.7	−1.9	−4.3
Current high blood pressure	20.7	19.6, 21.7	21.6	20.6, 22.7	0.9	4.3
Current high cholesterol	16.9	16.0, 17.9	17.7	16.8, 18.7	0.8	4.7
Sufficient servings of vegetables per day (adults)	11.7	10.9, 12.6	11.1	10.3, 11.9	−0.6	−5.1
Having at least 1 day off from usual activities due to health	13.7	12.1, 15.4	14.5	12.7, 16.4	0.8	5.8
Sufficient servings of vegetables per day (children)	14.1	13.2, 15.0	16.5	15.6, 17.5	2.4	17.0
Current smoker	12.8	11.9, 13.6	16.3	15.4, 17.3	3.5	27.3
Having takeaway (carryout) 3 or more times per week	1.9	1.6, 2.3	2.5	2.2, 2.9	0.6	31.6
Smoking in home occasionally or all the time	4.7	4.0, 5.4	6.5	5.7, 7.3	1.8	38.3
Food supply insecure	3.2	2.8, 3.7	6.1	5.6, 6.7	2.9	90.6
Other health-related issues (financial situation, unable to save)	28.2	27.1, 29.2	31.6	30.5, 32.7	3.4	12.1

Abbreviation: CI, confidence interval.
[a] All prevalence values are estimates.

Australians with an 85.9% response rate. Both of these surveys use poststratification methods to calculate their survey weights and include mobile-only households in their sampling frame.

RESULTS

When compared with census estimates, the unweighted age distribution of SAMSS had a higher proportion of older people and a lower proportion of younger people, as well as a higher proportion of females (Table 2). SAMSS had a lower proportion of people who rent, were employed, or were unemployed and a higher proportion who were born in Australia or the United Kingdom, married or living with a partner, and economically inactive. Poststratification weighting reduced the differences for dwelling status, employment status, and marital status.

Table 3 demonstrates the effect on the prevalence estimates for fair or poor health, diabetes, current smokers, and current high blood pressure of including the 9 variables, cumulatively, in the raked weights. All 4 of the prevalence estimates changed, as expected, when the typical age, sex, and area of residence variables were included in the raked and poststratification weights. When the other sociodemographics were added, individually or as a whole, the prevalence of diabetes and current high blood pressure changed slightly. The prevalence of self-reported fair or poor health increased when dwelling status (rent vs. other) and number of people in the household were included in the raked weights, and it increased by almost 3% with all 9 variables included in the raked weights. This pattern was similar for prevalence of current smokers, where the prevalence estimate increased by almost 2% with the addition of dwelling status and number of people in the household and a further 2% when all 9 variables were applied in the raked weights.

Table 4 shows the differences and percentage differences in the prevalence estimates between poststratification and fully raked weights on a range of selected health conditions, behavioral health risk factors, and socioeconomic conditions. More than half of the variables showed minimal differences in their prevalence when fully raked weights were applied compared with using the poststratification weight.

Table 5 shows the estimates from SAMSS using both poststratified and raked weights and the estimates from the face-to-face surveys. Little difference is seen in the estimates for current asthma (SAMSS and HOS) and sufficient daily consumption of vegetables (SAMSS and AHS). The raked-weight estimates for diabetes, arthritis, psychological distress, current smokers, and undertaking sufficient physical activity are similar to the estimates from HOS and AHS, in contrast to the

Table 5. Comparison of Prevalence Estimates From Poststratified and Raked Weights With Face-to-Face Surveys, Australia, 2011–2013

	South Australian Monitoring and Surveillance System, 2013		South Australia Health Omnibus Survey, 2013 (n = ~3,000)[a]	Australian Health Survey, 2011–2012 (South Australia Results Only) (n = 2,508)[b]
	Poststratified Weights	Fully Raked Weights		
Fair or poor health (self-rated), %	15.4	18.1		14.7
Diabetes, %	7.7	8.4	8.5	
Osteoporosis, %	4.5	4.7	6.0	
Arthritis, %	20.6	23.0	22.0	
Current asthma, %[c]	12.0	12.9	12.7[d]	
Psychological distress (Kessler 10), %	8.8	11.3		11.4
Body mass index				
Overweight and obese, %	58.9	61.5	58.6	
Normal, %	38.6	36.3	39.5	
Missing data, %	6.1	6.1	9.4	
Current smokers, %	12.7	16.3	16.7[e]	16.6
Sufficient physical activity, %[f]	41.6	40.4	39.7	
Sufficient daily consumption of fruit, %[f]	44.2	42.4		46.1
Sufficient daily consumption of vegetables, %[f]	11.7	11.1		10.0

[a] From reference 58.
[b] From reference 59.
[c] Have you ever been told by a doctor that you have asthma? Do you still have asthma?
[d] 2011 Health Omnibus Survey estimates.
[e] 2012 Health Omnibus Survey estimates.
[f] Persons aged18 years or more.

poststratification estimates. The poststratification weight estimates for self-reported fair or poor health, overweight and obesity, and sufficient daily consumption of fruit are closer to the estimates from HOS and AHS compared with the raked estimates.

DISCUSSION

This study highlights that using the statistical weighting formula, raked weights can improve health and behavioral risk factor estimates by incorporating a range of sociodemographic variables to overcome bias in telephone surveys. With declining response rates and inadequate sampling frames, specific groups of the community (e.g., people who rent) are often underrepresented in telephone surveys that can result in an under- or overestimation of the prevalence of health indicators. These findings imply that, for some health estimates, the limited sociodemographics incorporated in poststratification weighting methods (age groups, sex, and area of residence) are not sufficient to reduce bias in health estimates of the general population. By incorporating the 6 additional sociodemographic variables in the raked weighting formula into surveillance data, this study has demonstrated that the estimates are more in line with the more expensive national and state-based face-to-face surveys. The raked-weighting methodology has made it relatively easy to add many sociodemographic variables, which was not possible with the traditional poststratification weighting methods.

To our knowledge, this study is the first of its kind in the Australian context. It is unique in having a large sample, so that the conclusions are likely to be generalizable to the Australian population and are also applicable internationally, given that many of the issues regarding bias in telephone surveys are similar (16, 17). Most international studies of this kind are from the United States using BRFSS data (12, 60–64). Our study used sociodemographic variables in the raked weights similar to those of BRFSS (65) with but a few minor differences. Our study used country of birthplace instead of race because race is not commonly used or collected in Australian health surveys. Similar findings included the following: minimal prevalence differences in diabetes, cardiovascular diseases (heart attack, stroke), and current asthma (60–63) (<1% differences) and large differences in prevalence estimates (1%–3%) for overweight and obesity, fair or poor health, and physical activity. The difference between current smoking estimates in our study was 3.6%, which is less than the differences of 6%–7% reported in the BRFSS (12, 60–63).

Comparing the raked health estimates with 2 face-to-face surveys (both include mobile-only households that are excluded from telephone surveys and used poststratification weights) produced mostly similar but some mixed results. Similar estimates were found for arthritis, psychological distress, current smokers, diabetes, vegetable consumption, and sufficient levels of physical activity. The prevalence of sufficient servings of fruit suggests that using raked weights (42.4%) moved away from the AHS estimate (46.1%). The higher prevalence in the AHS compared with the SAMSS, even though the questions were the same, could be explained by the additional interviewer prompt in the AHS and the inclusion of tomatoes in the definition of fruit (66). Similarly, the raked weighted estimates for overweight and obesity (61.5%) were different from poststratification weights (58.9%) compared with HOS (58.6%). A possible explanation could be the larger proportion missing data from HOS (9.4%) compared with SAMSS (6.1%). The raked weighted estimate for fair or poor health (18.1%) was higher than the AHS estimate (14.7%). This difference could be attributable to mode effect; that is, people tend to report more socially desirable responses on the basis of survey mode. It has been suggested that, for nonfactual questions such as self-rated health or quality-of-life type questions, the physical presence of an interviewer can cause the respondent to give a more positive rating of their health (67).

Although some of the estimates examined in this study did not change when raked weights were applied, there were large changes in the estimates occurring among health indictors that were strongly related to groups underrepresented in telephone surveys because of noncoverage (exclusion of mobile-only households) and nonresponse, such as people who rent and young people (Table 1). Previous studies have shown that health estimates, with higher prevalence among socioeconomically disadvantaged households or younger people, can be underestimated in telephone surveys because of nonresponse bias (noncoverage and lower response rates) (23, 30). This is shown in our study where substantial changes occurred in the health estimates for food insecurity, mental health conditions, fair or poor health, overweight and obesity, and not sufficiently active. These estimates changed considerably with the addition of dwelling status (rent vs. other) in the raked weights (Table 3). This suggests the raked weights better adjust these estimates by eliminating some of the bias due to nonresponse and sampling coverage problems. However, if the current trends of mobile-only households continue to increase (25), then other efficient sampling strategies for chronic disease and surveillance systems may need further investigation to include the sociodemographic groups that are underrepresented in telephone surveys. As it stands, the current suggested methodologies for use in Australia that include mobile-only households in the sample frame (24, 68) are not feasible or sustainable and are too costly for use in SAMSS and similar systems.

The study design is robust because of the large, representative, statewide samples used and the large range of health conditions and health-related risk factors assessed. The raked-weighting methodology reliant on data from the census, which is conducted every 5 years, can be seen as a limitation. However, further analysis revealed minimal changes between the 2006 Census and the 2011 Census. Another limitation is that some sociodemographic variables or categories, which were considered important, could not be included because of insufficient sample size, such as Aboriginal and/or Torres Strait Islander status. Other limitations occurred when the question or categories were not comparable between SAMSS and the census, such as never married, separated, or divorced, or when the proportion of missing data was too high, such as for household income. It should also be noted that use of the census as the benchmark could also be introducing additional biases because of respondent error, processing error, partial or nonresponse, and undercount since the census is a self-completed survey. About 3.7% of the census forms were not returned

from a private dwelling in 2011, and the count data were imputed on the basis of similar dwellings in the surrounding area. Variable item nonresponse for South Australia ranged from 0.9% to 14.2% with a median rate of 4.5%, and the variables that had high nonresponse were residential status in a nonprivate dwelling, that is, communal type of accommodations (14.2%) (not used in this study), and the highest year of school completed (7.5%) (used with other training and education variables). Given that around 5% of the census data items used in the raking methodology are imputed, we are confident that the estimates would be slightly biased.

The use of a raking weighting methodology has overcome, to some extent, the nonresponse bias associated with the sampling methodology of telephone surveys. Raking methodology has the advantage over poststratification methods for surveillance data from a relatively small sample size and the option to incorporate more sociodemographic variables. Our results suggest that raking methodology for telephone surveys requires additional sociodemographic variables besides the usual age, sex, and area that were previously used and that the estimates correspond well with those from face-to-face surveys. Surveillance systems are always evolving to accommodate technological and societal changes. Implementing raked weights in surveillance systems will change the prevalence of some estimates and will cause breaks in trend data. Therefore, strategies are needed to educated users on

the changes in methodology to avoid misinterpretation of the findings.

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APPENDIX

Raked Weight Adjustment Methods

The raking steps are as follows:

Set weight = design weight.

Repeat the following steps until reached tolerance level for all margins or the number of iterations = 60.

For each v margin variable

Calculate weighted sample total = sum(weight);

Calculate weighted totals for each category in variable v = sum($\text{weight}_{v\ \text{categories}}$);

Weight = weight × % $\text{population}_{v\ \text{categories}}$ / [sum($\text{weight}_{\text{v categories}}$)/sum(weight)];

End

Trim weights;

Rescale weight if weighted sample total is not equal to total unweighted sample size;

End

By use of the following notations where n is the total sample size; N is the total population size (census); v denotes variable; u denotes category; k is the number of variables; j is the number of categories within variable v; T_v is the population proportion (control totals) calculated for each category, j, in variable, v; i is the individual in the sample, n; m is the number of iterations; and ${w_i}^{(m,v)}$ is the weighting variable for individual i at iteration m and variable, v, the raked weights are calculated as follows:

Initialize;

$T_v = N_{v,u}/N_v$, calculate the population control totals for each $v = 1, \ldots, k$ variables each with $u = 1, \ldots, j$ categories;

$m = 0$, initialize iteration variable;

${w_i}^{(0,0)}$ = design weight, set the weight variable to the sample design weight

For iteration 1, $m = 1$, do the following for each v margin variable ($v = 1, \ldots, k$):

Do the following for each u categories ($u = 1, \ldots, j$):

$$ {w_i}^{(1,k)} = {w_i}^{(1,k-1)} \times T_k \times \left(\frac{\sum {w_{i,k,u}}^{(1,k-1)}}{\sum {w_{i,k}}^{(1,k-1)}} \right). $$

Reiterate the above calculations until the tolerance level has been reached for all k margins (i.e., $T_k - (\sum {w_{i,k,u}}^{(m,k)} / \sum {w_{i,k}}^{(m,k)}) < 0.025$; or the number of iterations, m, has been reached such as 60:

For iteration, m, do the following, where $v = 1, \ldots, k$

Do the following for each u category ($u = 1, \ldots, j$):

$$ {w_i}^{(m,k)} = {w_i}^{(m,k-1)} \times T_k \times \left(\frac{\sum {w_{i,k,u}}^{(m,k-1)}}{\sum {w_{i,k}}^{(m,k-1)}} \right). $$

Poststratification Weight Adjustment Methods

The traditional poststratification weighting (or cell weighting) applied for each individual (which includes the design weight in the formula), each month is

$$w_{h,i} = d_{h,i} \times \frac{N_h}{\sum_{i=1}^{n_h} d_{h,i}} \times \frac{n}{N},$$

where N is the total population size; n is the total sample size; h is the stratum, age groups × sex × area of residence; N_h is the population size of stratum h; n_h is the sample size in stratum h; $w_{h,i}$ is the weighting value for respondent i in stratum h; and $d_{h,i}$ is the household size for respondent i in stratum h.