EPIDEMIOLOGY

Mortality Effects of Hypothetical Interventions on Physical Activity and TV Viewing

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ABSTRACT

YANG Y., A. M. HODGE, P.-A. DUGUÉ, E. J. WILLIAMSON, P. A. GARDINER, E. L. M. BARR, N. OWEN, D. W. DUNSTAN, B. M. LYNCH, and D. R. ENGLISH. Mortality Effects of Hypothetical Interventions on Physical Activity and TV Viewing. *Med. Sci. Sports Exerc.*, Vol. 53, No. 2, pp. 316–323, 2021. **Introduction:** Long-term effects of physical activity and television (TV) viewing on mortality have been inferred from observational studies. The associations observed do not allow for inferences about the effects of population interventions and could be subject to bias due to time-varying confounding. **Methods:** Using data from the Australian Diabetes, Obesity and Lifestyle Study, collected in 1999–2000 (T0), 2004–2005 (T1), and 2011–2012 (T2), we applied the parametric g-formula to estimate cumulative risks of death under hypothetical interventions on physical activity and/or TV viewing determined from self-report while adjusting for time-varying confounding. **Results:** In the 6377 participants followed up for 13 yr from 2004 to 2005 to death or censoring in 2017, 781 participants died. The observed cumulative risk of death was 12.2%. The most effective hypothetical intervention was to increase weekly physical activity to >300 min (risk ratio (RR), 0.66 (0.46–0.86) compared with a "worst-case" scenario; RR, 0.83 (0.73–0.94) compared with no intervention). Reducing daily TV viewing to <2 h in addition to physical activity interventions did not show added survival benefits. Reducing TV viewing alone was least effective in reducing mortality (RR, 0.85 (0.60–1.10) compared with the worst-case scenario; RR, 1.06 (0.93–1.20) compared with no intervention). **Conclusions:** Our findings suggested that sustained interventions to increase physical activity could lower all-cause mortality over a 13-yr period, and there might be limited gain from intervening to reduce TV viewing time in a relatively healthy population.
Key Words: TIME-VARYING CONFOUNDING, HYPOTHETICAL INTERVENTIONS, G-FORMULA, COHORT STUDY

Both insufficient physical activity (i.e., not meeting physical activity recommendations) and sedentary behavior (time spent sitting, as distinct from lack of physical activity) contribute to risk of chronic disease and mortality. In the absence of evidence from randomized trials to quantify the long-term effects of changes in physical activity and sedentary behavior, understanding how they are jointly related to mortality could be enhanced by better exploiting data from observational studies (1).

Insufficient physical activity and time spent in sedentary behaviors, particularly television (TV) viewing, have been associated with higher all-cause mortality in observational studies (2,3). These studies have typically measured exposures and

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confounders at a single time point, so they did not assess the possible effect of exposure changes over follow-up. We have previously highlighted (4) that in studies that used data from multiple time points, conventional regression analyses can be problematic in the presence of time-varying confounding when the values of confounding variables are influenced by past exposures (e.g., sedentary behavior affects adiposity, which in turn affects physical activity at the next time point) (5,6). When there is time-varying confounding, conditioning on confounders (e.g., adiposity) that also lie in a causal pathway in standard regression models can produce biased estimates (Figure, Supplemental Digital Content 1, which illustrates an example of time-varying confounding affected by prior exposure, http://links.lww.com/MSS/C89) (7). Alternative methods such as inverse probability weighting of marginal structural models have been used to estimate causal effects of physical activity while adjusting for such time-varying confounding (8–12). No published studies on sedentary behavior with multiple observation points have accounted for time-varying confounding.

Insufficient physical activity and sedentary behavior can be viewed as separate risk factors with distinct sociodemographic and behavioral contexts and correlates (13). Our aim was to estimate the effects of single or joint hypothetical interventions for insufficient physical activity and a common leisure-time sedentary behavior, TV viewing, on all-cause mortality over an approximate 13-yr period, while accounting for time-varying confounding, using the parametric g-formula. We used the parametric g-formula because it allows for estimation of the causal effects of complex population interventions, which could inform policy more directly compared with a typical exposure effect (14).

METHODS

Study population. The Australian Diabetes, Obesity and Lifestyle Study (AusDiab) is a population-based cohort study conducted in the six states and the Northern Territory of Australia. Details about the cohort have been described (15). Briefly, participants aged at least 25 yr were recruited in 1999–2000 (T0), then followed up in 2004–2005 (T1) and 2011–2012 (T2). Each data collection involved an initial household interview, followed by a biomedical examination and the administration of questionnaires. In the present study, we used T1 (2004–2005) as baseline in order to have information on prebaseline exposure and confounder history. Participants who attended T1 data collection (n = 6400) were included in this analysis. Participants who were pregnant (n = 23) at data collections were excluded, which left 6377 participants eligible for the analysis. The study was approved by the ethics committee of the International Diabetes Institute, and all participants provided informed consent.

Exposure measurements. Self-reported frequency and duration of leisure-time physical activity during the previous week were measured using the Active Australia Survey (16). The questions have been shown to have good reliability and validity (16). Physical activity consisted of walking for recreation or transport, and moderate-intensity and vigorous-intensity physical activity at leisure time. Total weekly recreational physical activity time ($\text{min}\cdot\text{wk}^{-1}$) was calculated as the sum of the time spent walking continuously for at least 10 min, time performing moderate physical activity, and double the time spent in vigorous physical activity ($\text{Time}_{\text{LTPA}} = \text{Time}_{\text{walk}} + \text{Time}_{\text{moderate}} + 2 \times \text{Time}_{\text{vigorous}}$) (16). The total time of weekly physical activity during leisure time was later used to simulate hypothetical interventions.

Participants were asked to self-report time spent watching TV or videos in the last 7 d, but to exclude the time that this occurred while performing other activities such as preparing a meal or doing other household chores. This method has been shown to provide reliable and valid estimates of TV viewing time among adults (17). Average daily TV viewing hours ($\text{h}\cdot\text{d}^{-1}$) was calculated.

Confounder measurements. Information on demographic attributes (sex, baseline age, country of birth, and level of education), self-reported history of health conditions (high cholesterol, high blood pressure, heart disease, and diabetes), and smoking status was obtained by an interviewer-administered questionnaire (15). Total cholesterol, hypertension, and diabetes status were also measured in the biomedical examinations. However, we used the self-reported history of diagnosis, assuming that awareness of prior health conditions would have more influence on an individual's lifestyle behaviors. Quintiles of an area-based index of relative socioeconomic advantage and disadvantage were calculated based on participants' postcode of residence (18). Alcohol and dietary intake were assessed using a self-administered, validated food frequency questionnaire. Mediterranean diet score was computed and used as a measure of overall diet quality (19). General health was assessed using the self-administered 36-Item Short Form Survey (SF-36) questionnaire. Waist circumference was measured by trained staff (15). We used waist circumference instead of body mass index because there is evidence it is a stronger predictor of all-cause mortality than body mass index (20).

Death ascertainment. Vital status and date of death were determined by linkage to the Australian National Death Index. Participants were followed up until the date of death or administrative end of follow-up on April 17, 2017.

Hypothetical interventions. We considered the following hypothetical interventions at T1 and T2, based on guidelines for physical activity (21) and the associations between TV viewing time and metabolic biomarkers (22): increasing weekly physical activity to sufficient (i.e., 150–300 min) if insufficiently active (i.e., <150 min), increasing weekly physical activity to optimal (i.e., >300 min) for all participants, reducing daily TV viewing to <2 h for all participants, increasing weekly physical activity to sufficient if insufficiently active and reducing daily TV viewing to <2 h, and, increasing weekly physical activity to >300 min and reducing daily TV viewing to <2 h for all participants.

In addition, for comparison, we considered a no-intervention scenario in which physical activity level and TV viewing time were allowed to evolve naturally (typically referred to as the "natural course"), and a scenario where weekly physical activity decreased to less than 30 min and daily TV viewing increased to 4 h or more for all participants (i.e., worst-case scenario).

Statistical analysis. We used the parametric g-formula to estimate the 13-yr cumulative risk of death under various hypothetical interventions on physical activity and/or TV viewing. The parametric g-formula is a generalization of standardization for time-varying exposures and confounders and can be used to estimate the standardized risk of death for hypothetical interventions under the assumptions of no unmeasured confounding, no measurement error, and no model misspecification (6). The standardized risk is estimated by a weighted average of the risks of death conditional on the given intervention and the observed confounder history. The weights are probability distribution functions of the time-varying confounders estimated using parametric regression models. The weighted average is approximated through Monte Carlo simulation (23). We implemented the parametric g-formula in two steps. First, parametric models were fitted to model conditional probabilities of physical activity, TV viewing, and each of the following time-varying confounders in the order listed: self-reported history of high cholesterol (yes, no), high blood pressure (yes, no), heart disease (yes, no), and diabetes (yes, no), and self-reported general health status (excellent, very good, good, fair, poor); waist circumference (normal, <94 cm (male) or <80 cm (female); increased risk, 94 to <102 cm (male) or 80 to <88 cm (female); greatly increased risk, ≥102 cm (male) or ≥88 (women) [24]), Mediterranean diet score (0–3, 4–6, 7–9 [19]), smoking status (never, former, current), and alcohol intake (grams per day: 0 (male and female), 1–39 (male)/1–19 (female), 40–59 (male)/20–39 (female), 60+ (male)/40+ (female) [25]). The models also included the following time-fixed confounders: sex (male, female), baseline age (in years), quintiles of an area-based index of relative socioeconomic advantage and disadvantage (18), country of birth (Australia or New Zealand, others), and level of education (university or technical institution, completed high school, some high school, primary/never attended school). See Table, Supplemental Digital Content 2, for details of models, http://links.lww.com/MSS/C90. These models were then used to simulate risk of death while setting physical activity and TV viewing to a specified intervention level in a Monte Carlo sample of the same size: 1) T0 and T1 confounder values were retained for all participants (T1 physical activity and TV viewing values were set to a specific level if part of an intervention); 2) risk of death before T2 was simulated; 3) for participants simulated to remain alive at T2 (physical activity and TV viewing were set to a specific level if part of an intervention, T2 values of confounders were simulated by comparing the predicted probability of the confounder value to a value randomly drawn from a standard uniform distribution, and risk of death from T2 to the end of follow-up was simulated); and 4) cumulative risk of death (i.e., 13-yr risk) was calculated as

$$P_{13\text{-yr}} = P_{\text{death before T2}} + (1 - P_{\text{death before T2}})\, P_{\text{death after T2}}.$$

For each hypothetical intervention, we compared the estimated 13-yr risk of death with the risk under the natural course (i.e., no-intervention scenario) and the risk under the worst-case scenario by calculating the risk ratios (RR) and risk differences (RD). We conducted the analyses separately in female and male participants to examine the possibility of effect heterogeneity by sex. We also compared simulated risk of death under the natural course with the observed risk as an informal validation of correct gross model specification.

Multiple imputation by chained equations was used to impute missing data (due to missing response to the questionnaire, or missing T2 attendance for those who were still alive at T2) under the assumption that data were missing at random; that is, the probability of data being missing did not depend on the unobserved data, conditioning on the observed data (26). For each hypothetical intervention, point estimates were averaged more than 40 imputed data sets, For the main analysis, 500 bootstrap samples were drawn for each imputed data set to estimate the standard errors (SE) and 95% confidence intervals (CI) were calculated using Rubin's rule (27,28); for sensitivity analyses, 200 bootstrap samples were used.

For comparison with a conventional approach, Cox regression with age as the time scale was used to estimate hazard ratios for mortality associated with baseline TV viewing and physical activity, adjusting for baseline confounders.

Statistical analyses were performed using Stata version 14.2 (StataCorp, College Station, TX) and Stata version 15 on the University of Melbourne's high-performance computing platform (Spartan).

RESULTS

A total of 6377 participants (54.7% female) were eligible. During 13 yr (73,518 person-years) of follow-up, 781 participants died (373 pre-T2 and 408 post-T2). Of participants who were alive at T2 ($n = 6004$), 20% did not attend T2 data collection. Participants who attended T2 were overall younger, were from more socioeconomically advantaged areas, and had higher educational qualifications compared with participants who were alive but did not attend T2; a higher proportion of them reported good to excellent health in general and no history of health conditions at T1 (Table, Supplemental Digital Content 3, characteristics of participants who were alive but did not attend T2, http://links.lww.com/MSS/C91).

Table 1 shows the characteristics of eligible participants at baseline (T1) and the potential time-varying confounders before and after baseline. Mean age at baseline was 56.5 yr. Three quarters (75.9%) were born in Australia or New Zealand, and 40.2% had tertiary education. At baseline, more than half of the sample were sufficiently active (57%) or watched less than 2 h of TV (54%; Table 1). Active participants tended to spend less time watching TV daily, although the differences were not large (Fig. 1).

Table 2 shows the 13-yr risks of death under various hypothetical interventions. The simulated 13-yr risk of death under no intervention (12.1%) was very similar to the observed risk (12.2%), indicating that the models were correctly specified overall. The hypothetical intervention that reduced 13-yr risk of death the most was to improve physical activity to

TABLE 1. Characteristics of participants included in the analysis, Australia.

	1999–2000 (T0; *n* = 6377)	2004–2005 (T1; *n* = 6377)	2011–2012 (T2; *n* = 4785[a])
Time-fixed covariates			
Baseline age, mean (SD), yr		56.5 (12.8)	
Sex, *n* (%)			
Male		2891 (45.3)	
Female		3486 (54.7)	
Born in Australia/New Zealand, *n* (%)		4839 (75.9)	
The Index of Relative Socio-economic Advantage and Disadvantage, *n* (%)			
1 (greatest disadvantage)		1084 (17.3)	
2		1296 (20.7)	
3		1291 (20.6)	
4		1204 (19.2)	
5 (greatest advantage)		1395 (22.2)	
Level of education, *n* (%)			
University or technical institution		2561 (40.2)	
Completed high school		1460 (22.9)	
Some high school		1966 (30.8)	
Primary or never attended school		390 (6.1)	
Baseline height, mean (SD), cm		167.6 (9.6)	
Time-varying covariates			
Weekly physical activity, *n* (%)			
<30 min	1257 (19.9)	1099 (17.4)	729 (15.8)
30–149 min	1686 (26.7)	1626 (25.7)	1127 (24.4)
150–300 min	1368 (21.6)	1480 (23.4)	1074 (23.3)
>300 min	2015 (31.9)	2118 (33.5)	1680 (36.4)
Daily TV viewing time, *n* (%)			
<2 h	3655 (57.7)	3385 (53.6)	2030 (52.7)
2–4 h	2225 (35.1)	2340 (37.0)	1478 (38.3)
≥4 h	459 (7.2)	595 (9.4)	347 (9.0)
Mediterranean diet score, *n* (%)			
0–3	1870 (29.3)	1922 (30.7)	1067 (29.7)
4–6	3766 (59.1)	3695 (59.0)	2127 (59.3)
7–9	741 (11.6)	651 (10.4)	394 (11.0)
Waist circumference[b], *n* (%)			
Normal	2500 (39.6)	2120 (33.3)	1057 (26.8)
Increased risk	1641 (26.0)	1654 (26.0)	1007 (25.5)
Greatly increased risk	2173 (34.4)	2584 (40.6)	1879 (47.7)
Smoking status, *n* (%)			
Never smoker	3686 (58.8)	3527 (58.0)	2657 (59.9)
Former smoker	1858 (29.6)	1982 (32.6)	1517 (34.2)
Current smoker	723 (11.5)	568 (9.3)	260 (5.9)
Alcohol intake, *n* (%), $g \cdot d^{-1}$			
0 (male and female)	940 (14.7)	836 (13.3)	481 (13.4)
1–39 (male)/1–19 (female)	4571 (71.7)	4470 (71.3)	2537 (70.7)
40–59 (male)/20–39 (female)	627 (9.8)	683 (10.9)	411 (11.5)
60+ (male)/40+ (female)	239 (3.7)	279 (4.5)	159 (4.4)
Self-reported general health, *n* (%)			
Excellent	603 (9.5)	689 (10.9)	426 (10.7)
Very Good	2346 (37.0)	2335 (36.9)	1522 (38.3)
Good	2633 (41.5)	2460 (38.8)	1552 (39.1)
Fair	693 (10.9)	755 (11.9)	422 (10.6)
Poor	74 (1.2)	95 (1.5)	51 (1.3)
History of health conditions, *n* (%)			
High cholesterol	1714 (27.0)	2654 (41.8)	3044 (58.1)
High blood pressure	1690 (26.6)	2399 (37.7)	2666 (51.5)
Diabetes	276 (4.3)	512 (8.0)	629 (12.9)
Heart conditions	443 (7.0)	559 (8.8)	218 (4.6)

Numbers across categories for some variables did not add up because of missing values.
[a]Number of participants attended T2, before multiple imputation was applied to impute missing data due to missing T2 attendance for those who were still alive at T2.
[b]Normal, <94 cm (male) or <80 cm (female); increased risk, 94 to <102 cm (male) or 80 to <88 cm (female); greatly increased risk, ≥102 cm (male) or ≥88 (women).

>300 $min \cdot wk^{-1}$ (RR, 0.83 (0.73–0.94) compared with the natural course; RR, 0.66 (0.46–0.86) compared with the worst-case scenario), followed by improving physical activity to 150–300 $min \cdot wk^{-1}$ for insufficiently active participants (RR, 0.92 (0.82–1.01) compared with the natural course; RR, 0.73 (0.52–0.94) compared with the worst-case scenario). The average percentages of participants who needed to improve their physical activity were 65.2% and 42.1%, respectively, for the two interventions. The intensive physical activity intervention would have prevented 20 deaths (95% CI, 7–33 deaths) per 1000 people in a 13-yr period compared with not intervening. Reducing daily TV viewing to <2 h alone was the least effective intervention for lowering mortality (RR, 1.06 (0.93–1.20) compared with the natural course; RR, 0.85 (0.60–1.10) compared with the worst-case scenario). Reducing daily TV hours jointly with any of the physical activity interventions required more people changing their behaviors (average of 80.7% and 68.2%, respectively) while not lowering the risk further.

Table 3 shows the 13-yr risk of death in male and female participants under the natural course, the worst-case scenario, and the joint intensive intervention. The effect of hypothetical interventions on mortality (i.e., RR) seemed to be similar for

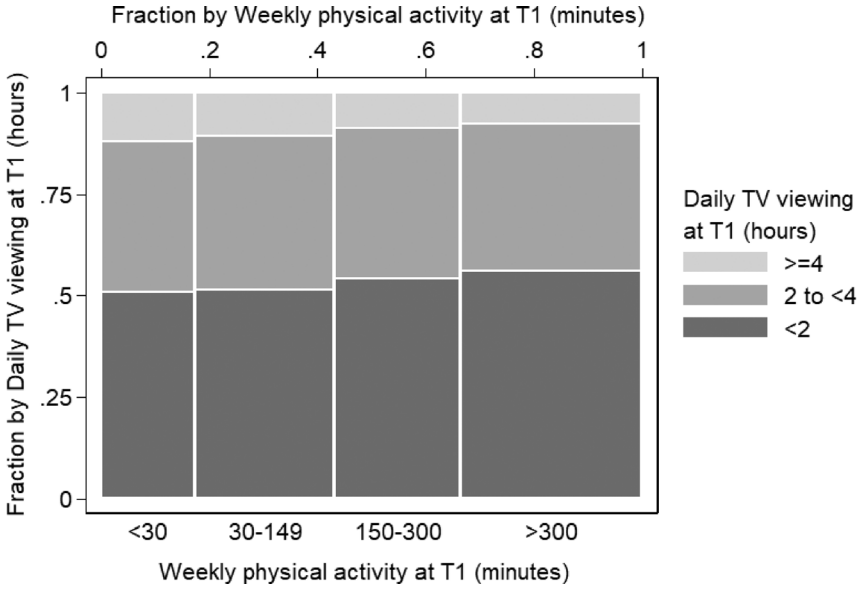

FIGURE 1—Plot of daily TV viewing and weekly physical activity at baseline (T1).

male and female participants. However, population RD was larger in male than in female participants because of higher absolute risks under the natural course.

We assumed correct ordering of exposures and time-varying confounders in our models. Our sensitivity analysis showed that results were robust to various modeling orders (Table, Supplemental Digital Content 4, estimated risk of death under various modeling orders of time-varying covariates, http://links.lww.com/MSS/C92).

We found that the usual method of analysis, which used only baseline data in a Cox regression model, underestimated the benefit of sustained higher physical activity compared with the g-formula, but the effect of TV viewing on all-cause mortality estimated from the g-formula was similar to the effect estimated from the Cox regression (Fig. 2).

DISCUSSION

Our results suggest that in this cohort of adults, mortality could have been lowered by sustained interventions that increased physical activity. The intervention that seemed most effective to reduce mortality compared with no intervention was to increase weekly physical activity to >300 min (the intensive physical activity intervention), followed by increasing physical activity to 150–300 min·wk^{-1} in people who were insufficiently active (the moderate physical activity intervention). Interventions that reduced TV viewing time alone or in addition to physical activity interventions did not show added mortality benefits.

Although the intensive physical activity intervention was the most effective in reducing mortality, it required more participants to modify their behavior to achieve the change (on average, 65% of participants needed to modify their physical activity levels at each time point), compared with the moderate physical activity intervention (42% on average needs to change). A systematic review found that relative reduction in all-cause mortality associated with higher physical activity was greater for women than for men (29), the effects of the hypothetical interventions on relative reduction in mortality were similar for women and men in our study. It should be noted that in real life incomplete adherence is likely, and our estimates correspond to the best-case scenario.

TABLE 2. Risks of death under hypothetical interventions using the parametric g-formula.

No.		Interventions	13-yr Risk of Death (95% CI), %	Population RD (95% CI), %	Population RR (95% CI)	RD (95% CI), %	RR (95% CI)	Average % Needed Intervention[a]
0	Natural course	No intervention	12.1 (10.9 to 13.2)	Reference	Reference			0
1	Worst-case scenario	Reducing physical activity to <30 min·wk^{-1} and increasing TV viewing to ≥4 h·d^{-1} for all	15.2 (11.6 to 18.9)	3.2 (–0.4 to 6.8)	1.26 (0.96 to 1.57)	Reference	Reference	97.6
2	Physical activity only, moderate	Increasing physical activity to 150–300 min·wk^{-1} if <150 min·wk^{-1}	11.1 (9.7 to 12.4)	–1.0 (–2.2 to 0.2)	0.92 (0.82 to 1.01)	–4.2 (–8.2 to –0.2)	0.73 (0.52 to 0.94)	42.1
3	Physical activity only, intensive	Increasing physical activity to >300 min·wk^{-1} for all	10.0 (8.6 to 11.5)	–2.0 (–3.3 to –0.7)	0.83 (0.73 to 0.94)	–5.2 (–9.3 to –1.1)	0.66 (0.46 to 0.86)	65.2
4	TV viewing only	Reducing TV viewing to <2 h·d^{-1} if ≥2 h·d^{-1}	12.8 (11.1 to 14.6)	0.8 (–0.9 to 2.4)	1.06 (0.93 to 1.20)	–2.4 (–6.6 to 1.8)	0.85 (0.60 to 1.10)	48.4
5	Joint, moderate	Intervention nos. 2 and 4	11.6 (9.8 to 13.3)	–0.5 (–2.1 to 1.1)	0.96 (0.83 to 1.09)	–3.7 (–8.0 to 0.7)	0.76 (0.52 to 1.01)	68.2
6	Joint, intensive	Intervention nos. 3 and 4	10.5 (8.7 to 12.4)	–1.5 (–3.3 to 0.2)	0.87 (0.73 to 1.02)	–4.7 (–9.2 to –0.2)	0.70 (0.46 to 0.93)	80.7

The observed 13-yr risk of death was 12.2%; 500 bootstrap samples were drawn for each of the 40 imputed data sets to estimate the SE and 95% CI.
[a]Average percentage of participants who need to be intervened on at T1 and T2.

TABLE 3. Risk of death under hypothetical interventions in women and men.

Interventions	13-yr Risk of Death (95% CI), %	Population RR (95% CI)	Population RD (95% CI), %	RR (95% CI)	RD (95% CI), %
Women					
Natural course	9.9 (8.4 to 11.3)	Reference	Reference		
Worst-case scenario	12.5 (8.0 to 16.9)	1.27 (0.83 to 1.70)	2.6 (–1.6 to 6.8)	Reference	Reference
Joint, intensive	8.7 (6.1 to 11.3)	0.88 (0.61 to 1.15)	–1.2 (–3.8 to 1.4)	0.70 (0.31 to 1.09)	–3.8 (–9.6 to 2.0)
Men					
Natural course	14.7 (13.1 to 16.4)	Reference	Reference		
Worst-case scenario	19.1 (12.9 to 25.2)	1.30 (0.88 to 1.71)	4.3 (–1.8 to 10.5)	Reference	Reference
Joint, intensive	12.7 (9.7 to 15.7)	0.86 (0.68 to 1.04)	–2.0 (–4.7 to 0.7)	0.67 (0.36 to 0.98)	–6.4 (–14.0 to 1.3)

The observed 13-yr risks of death were 9.8% for women and 15.2% for men; 200 bootstrap samples were drawn for each of the 40 imputed data sets to estimate the SE and 95% CI.

Like other analyses of observational data, these estimates are based on the assumptions of no unmeasured confounding, no measurement error, and no model misspecification. We cannot exclude the possibility of unmeasured confounding despite adjusting for several important confounders. Self-reported time spent in physical activity and in TV viewing are subject to measurement error. However, the questionnaires used in our study were previously shown to have good reliability and acceptable validity for estimates of the true exposure level (16,17). We acknowledge the possibility of misspecification of parametric models and functional forms of the past covariate history included as independent variables. However, we were able to closely reproduce the observed risk of death under the natural course, which is a necessary condition for no overall model misspecification under no intervention. The parametric g-formula requires fitting multiple models; therefore, it may be more sensitive to violations of the aforementioned assumptions, as violation in one model may accumulate through the others (23). The parametric g-formula is subject to the "g-null paradox"; i.e., the null hypothesis (in our case, this is that interventions on physical activity and TV viewing have no effect on all-cause mortality), even if true, will be rejected in a large enough sample because the estimated value of the g-formula for the outcome generally depends on the exposure history (30). However, in practice, the g-null paradox is of less concern compared with typical random variability (31). Finally, the imputation of missing data relied on the missing-at-random assumption, which was reasonably plausible given the extensive risk factor information collected at each time point.

Current public health guidelines recommend minimizing sedentary behavior and doing at least 150 min·wk^{-1} of moderate-to-vigorous-intensity physical activity, or 300 min·wk^{-1} for additional health benefit (32–34). These recommendations are mainly based on studies of associations between exposures at a single time point and risk of health outcomes such as cardiovascular health and cancer (33). Our study, on the other hand, estimated the potential effect on mortality had these two risk factors been altered by sustained population interventions. This is the key strength of our study because it is rarely feasible to estimate such causal effects for a generally healthy population

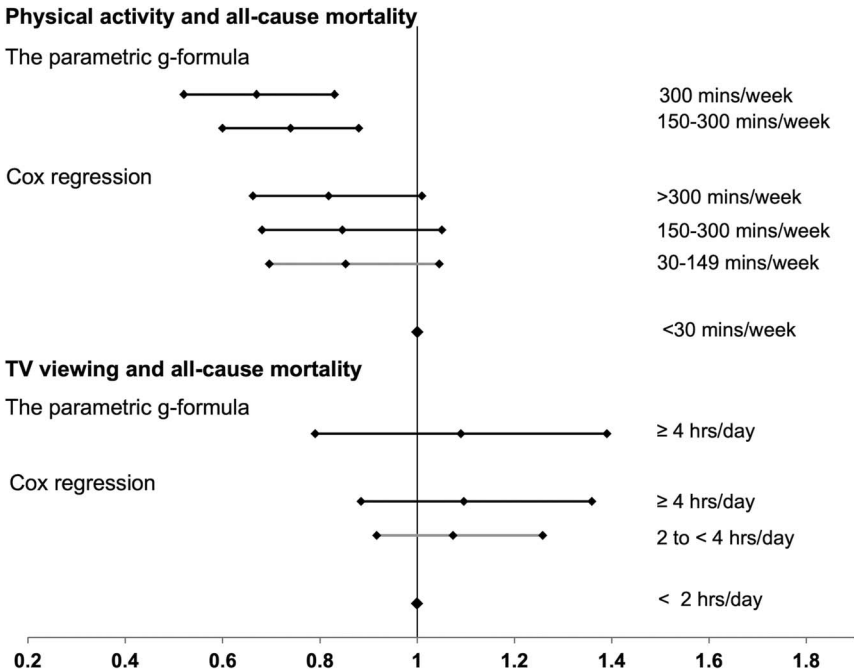

FIGURE 2—Effects of TV viewing and physical activity on all-cause mortality, estimated by the g-formula and Cox regression. The parametric g-formula (RR and 95% CI) adjusted for time-fixed and time-varying confounding. RR values for the "2 to <4 h" TV viewing category and the "30–149 min·wk^{-1}" physical activity category were not presented because we did not simulate these hypothetical interventions. Cox model (hazard ratio and 95% CI) adjusted for baseline (T1) confounders (i.e., typical adjustment of baseline confounders). Five imputations were used because of 5% T1 missing data. For comparison, "<2 h" TV viewing and "<30 min·wk^{-1}" physical activity were used as reference categories in both the parametric g-formula analysis and the Cox model.

through randomized controlled trials (1). Our finding demonstrated that using a single measurement of physical activity is likely to underestimate the protective effects of physical activity. This may stimulate additional public health expenditure into physical activity promotion. Health promotion programs frequently incorporate physical activity promotion into programs to address obesity prevention or reduction. Our research (which accounts for obesity-related time-varying confounding) highlights that physical activity itself is important for longevity. Although other g-methods such as inverse probability weighted marginal structural models could also overcome the bias from time-varying confounding affected by past exposure through generating a pseudopopulation in which exposure is independent of confounders, the parametric g-formula has the advantage of generating counterfactual outcomes under different exposure scenarios that involve multiple interventions such as increasing physical activity *and* reducing TV time (7).

Previous findings from the AusDiab study reported that watching ≥4 h of TV daily was associated with higher all-cause mortality (35). Our Cox model showed a weaker association in the same direction between TV viewing time at T1 and all-cause mortality (Fig. 2). This could be partly because the previous study used T0 as baseline, whereas we used T1 as baseline. Our sample was smaller because of loss to follow-up between T0 and T1, and healthier. The prevalence of self-reported excellent and very good health status was slightly lower in participants than in the general Australian population (36). However, the participants were more physically active than the general Australian population of the same age—about 50% at T0 reported sufficient levels of activity (Table, Supplemental Digital Content 5, prebaseline characteristics of participants by baseline attendance status, http://links.lww.com/MSS/C93) compared with about 40% for the population (37). Thus, our findings might be most applicable to physically active people. In our sample where daily TV viewing hours were already less than 2 h for more than half of the participants, we estimated no further survival benefit by intervening on this exposure. Over the 12 yr between T0 (1999/2000) and T2 (2011/2012), there was an expansion of TV viewing options and other domestic entertainment and screen-based technologies, which may have reduced the relevance of our exposure variable. Although our estimates are not directly comparable to results from studies using conventional regression approaches, our findings and those of studies using regression approaches suggest protective effects of physical activity on mortality (29). Furthermore, we found that using only baseline data could underestimate the potential benefit of long-term physical activity.

Although we used repeatedly measured exposure data, the analyses would have benefited from more time points at regular intervals, which are more representative of sustained interventions over time. We coarsened the time spent in physical activity and TV viewing into categories relevant to current public health guidelines. This may affect the interpretation of our findings because of multiple versions of treatment (38). For example, our hypothetical intervention "increasing physical activity to >300 min·wk^{-1}" can be achieved by increasing physical activity to 301 min or to 400 min through increasing activity duration or intensity over a week. Our estimates can be interpreted as a weighted average of the effects of the different versions, weighted by the probability of each version naturally arising within the population (38,39). It should be noted that our estimates may not be generalizable to populations with different distributions of physical activity and TV viewing level. Results from the Australian National Health Surveys showed that the percentage of Australian adults with sufficient physical activity (i.e., ≥150 min·wk^{-1}) remained low from 1989 to 2011 (39% in 1989 to 41% in 2011) (37). The hypothetical interventions we considered may have a greater benefit on lowering mortality in the general population than in our sample where close to 60% can be classified as "sufficiently active."

In conclusion, our findings suggest that sustained interventions on physical activity could lower all-cause mortality over a 13-yr period, and that there might be limited gain from intervening on TV viewing time in a relatively healthy population.

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Y. Y., A. M. H., P. A. D., B. M. L., and D. R. E. designed the study. Y. Y. performed the statistical analysis with support from E. J. W. Y. Y., A. M. H., P. A. D., B. M. L., and D. R. E. drafted the manuscript. P. A. G., E. L. M. B., N. O., and D. W. D. contributed to the data interpretation and provided critical feedback for each draft. All authors read and approved the final manuscript.

The authors declare that they have no relationship with companies or manufacturers who will benefit from the results of the present study. The results of the present study do not constitute endorsement from the American College of Sports Medicine. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

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