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RESEARCH REPORT

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Prospective association between e-cigarette use frequency patterns and cigarette smoking abstinence among adult cigarette smokers in the United States

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Abstract

Aims: To estimate the association of longitudinal patterns of e-cigarette use with cigarette smoking abstinence, after accounting for time-dependent confounding and selection bias.

Design: Secondary analysis of longitudinal national cohort data. Using marginal structural models and four waves of the population assessment of tobacco and health (wave 1, 2013–14; wave 2, 2014–15; wave 3, 2015–16; wave 4, 2016–18), we estimated the association of vaping frequency across waves 2 and 3 with 12-month sustained cigarette smoking abstinence at wave 4, adjusting for time-dependent confounders at waves 1 and 2 and selection bias due to drop-out with inverse probability of treatment and censoring weights.

Setting: United States.

Participants/cases: A total of 5699 adults (18+ years) who smoked cigarettes and did not vape at wave 1.

Measurements: The exposure was vaping frequency at waves 2 and 3 (non-use, non-daily use, daily use), representing nine possible combinations of vaping frequency across two waves. Non-use at both waves was the exposure reference group. The primary outcome was sustained 12-month cigarette smoking abstinence at wave 4.

Findings: Among 5699 adults who smoked cigarettes at wave 1, a total of 560 (9.8%) reported smoking abstinence at wave 4. Compared with nonuse at both waves, daily vaping at both waves [risk ratio (RR) = 3.82, 95% confidence interval (CI) = 2.59–5.64] and non-use at wave 2 followed by daily vaping at wave 3 (RR = 2.50, 95% CI = 1.66–3.77) were positively associated with smoking abstinence; non-daily vaping at both waves was inversely associated with smoking abstinence (RR = 0.28, 95% CI = 0.11–0.75). Results persisted after accounting for misclassification of e-cigarette use and cigarette smoking abstinence and after restricting to participants with plans to quit smoking.

Conclusions: In a US cohort of adult smokers, longitudinal patterns of vaping frequency appear to predict smoking abstinence, even after accounting for several sources of

systematic error. Consistent daily vaping is associated with increased chances of cigarette smoking abstinence, while consistent non-daily vaping is associated with decreased chances of smoking abstinence.

KEYWORDS
Confounding, e-cigarettes, marginal structural models, misclassification, selection bias, smoking cessation, vaping

INTRODUCTION

Evidence on whether e-cigarettes are an effective aid for quitting combustible cigarette smoking is variable [1–3]. While earlier randomized trials showed modest efficacy [4–8], recent large-scale trials report positive effects of e-cigarette use on cigarette smoking abstinence compared to no e-cigarette use or standard treatment (e.g. nicotine replacement therapy, counseling) [9–11]. In contrast, observational studies show mixed results. A 2020 meta-analysis reported a pooled odds ratio for the association between e-cigarette use and cigarette smoking abstinence of 1.10 [95% confidence interval (CI) = 0.94–1.28] among 31 observational longitudinal studies, indicating an average of no association with substantial heterogeneity (I^2 = 76.3%) [3]. Clear evidence from population-based observational cohort studies is important for understanding the real-world effectiveness of e-cigarettes for smoking abstinence in the general population under naturalistic conditions.

One explanation for inconclusive findings in observational studies may be due to imprecisely defining e-cigarette exposure [12]. Individuals who vape nicotine daily might be more likely than those who do not vape nicotine to achieve smoking abstinence, but non-daily vaping may have no effect or reduce likelihood of smoking abstinence [13–16]. Daily vaping could be more effective than non-daily vaping if greater nicotine delivery leads to reduced cigarette cravings. In contrast, non-daily vaping may result in continued dual use of both e-cigarettes and cigarettes and increased nicotine dependence, rather than full substitution of e-cigarettes for cigarettes [17, 18]. Studies that do not differentiate between vaping frequency may find null associations with smoking abstinence due to balancing of inverse and positive associations.

Additionally, heterogeneity in consistency of vaping over longer follow-up periods may impact the effectiveness of vaping for cigarette smoking abstinence [19, 20]. For example, vaping daily for 1 month may be less effective for smoking abstinence than vaping every day for 2 years or longer, particularly as most people take longer than 1 year to successfully quit smoking cigarettes [21]. Glasser *et al.* evaluated vaping patterns at three waves of the population assessment of tobacco and health (PATH) study and reported that individuals who used e-cigarettes daily at each wave, or increased to daily use over follow-up, were more likely than never users to report smoking abstinence [19]. It is important to identify which longer-term patterns of vaping are effective for sustained cigarette smoking abstinence, and whether differences exist by vaping frequency and duration of use.

When examining the association of longer-term vaping patterns with cigarette smoking abstinence using observational data, one must account for confounders (i.e. shared risk factors) that vary over time to estimate a valid effect [22, 23]. However, if time-varying confounders simultaneously act as mediators of vaping and cigarette smoking abstinence (i.e. time-dependent confounding), then use of traditional regression methods can bias estimates due to conditioning on causal intermediates or collider stratification bias [22, 23]. There are numerous factors that could affect e-cigarette use and smoking abstinence, but also be affected by prior vaping behaviors (i.e. function as both confounders and mediators), including smoking frequency and nicotine dependence. To appropriately adjust for time-dependent confounding researchers can use g-methods, including marginal structural models (MSMs) [22, 23].

The present study examines the association of e-cigarette use with cigarette smoking abstinence among US adults, accounting for vaping frequency and longer-term patterns of e-cigarette use. We assess the joint association between vaping frequency at two time-points and combustible cigarette smoking abstinence, reduction in cigarette smoking and abstinence from all tobacco products at the end of follow-up, accounting for time-dependent confounding using MSMs. We hypothesized that patterns of daily vaping would be associated with an increased probability of cigarette smoking abstinence and reduction, while patterns of non-daily vaping would be associated with a decreased probability of smoking abstinence and reduction.

METHODS

Study population and study design

We use four waves of deidentified public use data from the PATH study, a US national cohort study on tobacco product use and health. Between 2013 and 2014, PATH recruited 32 320 adult participants using a four-stage stratified area probability sample design. Participants completed computer-assisted follow-up interviews approximately every 12 months. The study design, sampling process and data collection methods for PATH have been described in detail previously [24].

The analytical sample included 5699 adults (aged ≥ 18 years) who were current established cigarette smokers and not currently using e-cigarettes at wave 1, and completed all four waves of data collection. Established cigarette smoking was defined as having ever smoked > 100 cigarettes (in a participant's life-time) and currently smoking cigarettes every day or some days at wave 1. Non-current e-cigarette

use was defined as currently using e-cigarettes 'not at all' at wave 1, and includes both never and former e-cigarette users (see Supporting information, Figure S1 for inclusion and exclusion flow-chart).

Measures

Primary outcome: cigarette smoking abstinence

The primary outcome was self-reported 12-month sustained cigarette smoking abstinence at the end of follow-up (wave 4, 2016–18), measured with the question: 'In the past 12 months, have you smoked a cigarette, even one or two puffs?'. Participants were coded as having the outcome (1) if they responded 'No' to smoking even one or two puffs of a cigarette in the past 12 months at wave 4 and zero (0) otherwise.

Secondary outcomes

Secondary outcomes included substantial reduction of average cigarette consumption and 12-month abstinence from all tobacco products (including e-cigarettes). Substantial reduction of cigarette consumption was defined as ≥ 50% reduction in average cigarettes smoked per day between waves 1 and 4. Twelve-month tobacco product abstinence was defined as no past 12-month use of cigarettes, e-cigarettes, cigars, hookah, pipe tobacco or smokeless tobacco at wave 4.

Exposure: e-cigarette use frequency

Exposure was frequency of current e-cigarette use measured at waves 2 and 3. Waves 2 and 3 data collection occurred approximately 1 year apart between 2014 and 2015 (wave 2) and 2015 and 2016 (wave 3). Daily e-cigarette use was defined as currently using e-cigarettes 'every day'; non-daily use was defined as currently using e-cigarettes 'some days' and non-use of e-cigarettes was defined as currently using e-cigarettes 'not at all'. We estimated the joint effect of vaping frequency at waves 2 and 3 on cigarette smoking abstinence at wave 4, representing nine possible patterns of e-cigarette use (Figure 1). Non-use at both waves was the reference group.

Confounders

We incorporated confounders measured at wave 1 and time-varying confounders measured at waves 1 and 2 that were variables associated with both e-cigarette use and smoking abstinence in prior literature. Time-varying confounder assessment occurred one wave prior to assessment of the exposure to ensure temporal precedence. Confounders measured at wave 1 included socio-demographic characteristics (age, sex, race/ethnicity, education, income, sexual identity) [25, 26] and baseline cigarette smoking duration. Time-varying

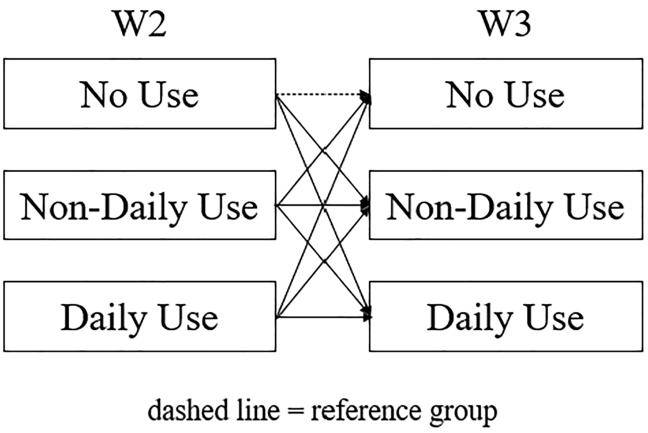

FIGURE 1 Nine e-cigarette use frequency patterns of exposure

confounders included cigarette smoking frequency/intensity, nicotine dependence (composite score of 16 items from the Wisconsin inventory of smoking dependence motives, nicotine dependence syndrome scale and DSM measure for impaired control) [27], intentions to quit smoking and cessation-related behaviors (i.e. quit attempts or use of cessation aids) [28], mental health symptoms [29, 30], other tobacco and substance use behaviors [31], attitudes/beliefs related to e-cigarettes [25], tobacco-related social norms [32], living with tobacco users [33] and diagnosis of tobacco-related diseases [34]. We included a total of 20 confounders (seven measured at wave 1 and 13 time-varying) as predictors in inverse probability weights (Supporting information, Table S1).

Analysis

Analyses were conducted using SAS version 9.4. The analysis was not pre-registered and should be considered exploratory. We calculated the prevalence of each outcome and the nine e-cigarette exposure patterns, and examined the distribution of confounders by exposure groups at each wave and by those retained versus lost to follow-up. MSMs were used to simultaneously estimate the effect of vaping frequency at two time-points on past-year smoking abstinence at wave 4 while adjusting for time-dependent confounding and selection bias due to dropout. MSMs incorporate inverse probability of treatment weights (IPTW) to create a pseudopopulation in which the distribution of confounders and past exposure is balanced by vaping frequency at each wave. Under assumptions of exchangeability, positivity, consistency and correct model specification [35, 36], MSMs estimate the average effect of each e-cigarette exposure pattern on cigarette smoking abstinence at wave 4 [22].

For each exposure measurement (two per participant), we estimated a stabilized weight equal to the inverse probability that a participant received the e-cigarette exposure history they received (e.g. non-use, non-daily use, daily use), given past exposure, smoking abstinence and covariates [37]. To obtain the weight denominator, a pooled multinomial logistic regression model estimated the predicted probability of

vaping frequency at waves 2 and 3. Independent variables included all time-invariant confounders, time-varying confounders measured at the prior wave, an indicator for time-varying past 12-month smoking abstinence prior to wave 4 and a variable for wave to allow for a time-specific intercept [37]. The same model estimated the weight numerator, excluding time-varying values of covariates. A similar approach estimated stabilized inverse probability of censoring weights (IPCW), which account for selection bias by creating a pseudopopulation in which loss-to-follow-up is random with respect to prior exposure and covariates [38]. The final weight was the product of the IPTW and IPCW at wave 3 (mean = 1.0, min. = 0.42, max. = 2.7). See Supporting information, Appendix S1 for weight calculation.

We estimated the joint effect of vaping frequency at waves 2 and 3 by fitting a weighted modified Poisson regression model to produce risk ratios (RR) and 95% CI comparing each e-cigarette exposure pattern to no current use at both waves (reference) [39]. We used PROC GENMOD and generalized estimating equations with an independent correlation matrix for standard errors robust to multiple observations per person (due to weighting). The model was weighted by the product of the IPTW and IPCW and included smoking abstinence at wave 4 as the binary outcome, and the following predictors: separate variables for vaping frequency at waves 2 and 3, an interaction term between vaping frequency at waves 2 and 3 and wave 1 confounders. See Supporting information, Figure S2 for causal diagram and Supporting information, Appendix S1 for MSM equation.

Sensitivity analyses

The analysis may overestimate the association if participants who vape are more motivated to quit smoking than those who do not vape. We repeated the primary analyses restricting the sample to participants with intentions to quit smoking during the next 12 months at wave 1. We additionally tested for effect modification on the relative scale by motivations to quit smoking by examining an interaction term between intentions to quit smoking and e-cigarette use frequency.

We performed a probabilistic bias analysis to quantify the effect of underreporting vaping frequency and overreporting 12-month smoking abstinence on results [40]. Individuals are unlikely to over-report tobacco-product use or under-report smoking abstinence [41]. Informed by validation studies and assuming non-differential misclassification [42–44], we defined trapezoidal distributions of misclassification probabilities for self-reported e-cigarette use (sensitivity range = 0.78–1.0, lower/upper mode = 0.85/0.875) and smoking abstinence (specificity range = 0.93–1.0, lower/upper mode = 0.95/0.975). We sampled from the distributions 1000 times and re-estimated MSMs using record-level Bernoulli trials for each iteration [45].

Secondary analysis

PATH is a complex survey allowing for estimates representative of the non-institutionalized civilian US population when sample weights are applied. Sample weights were not incorporated into the primary analysis because the goal of inverse probability weighting is to address internal validity rather than external validity (e.g. generalizability). A caveat to not using sample weights is that estimates are not necessarily generalizable to the US population and should be interpreted as the average treatment effect for the survey population. We conducted a secondary analysis to produce estimates of the average treatment effect for the US population of adults at wave 4 (2016–18). The final inverse probability weights were multiplied by PATH wave 4 sample weights [46]. We re-estimated associations using PROC SURVEYLOGISTIC and the balanced repeated replication method and Fay adjustment ($\rho = 0.3$) for robust standard errors.

Missing data

The Markov Monte Carlo method of multiple imputation with five imputed data sets was used to simulate values for missing data (Supporting information, Appendix S2). Data were missing for < 3% of participants, except for wave 1 other tobacco (4.3%), poverty level (7.0%), plans to quit smoking (38.6%, high percentage missing due to instrument error); wave 2 past 12-month quit attempt (10.1%) and plans to quit smoking (10.8%).

RESULTS

Among 5699 adults who smoked cigarettes and who were not currently using e-cigarettes at wave 1, a total of 560 (9.8%) reported 12-month abstinence from cigarettes at wave 4. Additionally, 1690 (29.7%) reported ≥ 50% reduction in cigarette consumption and 411 (7.2%) reported 12-month abstinence from all tobacco products (including e-cigarettes) at wave 4. All participants who reported 12-month abstinence were classified as substantially reducing cigarette consumption, except for 45 participants who reported smoking 0 cigarettes/day at wave 1. The most prevalent vaping pattern was no current e-cigarette use at both waves (n = 4521, 79.3%), followed by non-daily use at wave 2 and no current use at wave 3 (n = 497, 8.7%). Daily use at both waves represented 1.4% of participants (n = 79) (Table 1).

Compared to participants who reported no current e-cigarette use, participants who vaped with any frequency were younger (< 34 years), smoked cigarettes for shorter duration and were more likely to believe that e-cigarettes are less harmful than cigarettes, live with a tobacco user, use illicit drugs and have high internalizing mental health problems (Table 2). Compared to participants who vaped non-daily, participants who vaped daily had higher income and were heavier smokers with greater nicotine dependence. Participants who vaped daily were less likely to use other tobacco products or marijuana than participants who vaped non-daily. Retained participants were more likely to be female and have higher externalizing mental health problems than participants lost to follow-up (Supporting information, Table S2).

TABLE 1 Patterns of e-cigarette use over follow-up among 5699 adults who smoke cigarettes and do not currently use e-cigarettes at wave 1

E-cigarette use wave 2	E-cigarette use wave 3	*n* (%)
Non-use	Non-use	4521 (79.3)
Non-daily use	Non-use	497 (8.7)
Non-use	Non-daily use	231 (4.0)
Non-daily use	Non-daily use	157 (2.8)
Non-use	Daily use	90 (1.6)
Daily use	Daily use	79 (1.4)
Daily use	Non-use	59 (1.0)
Non-daily use	Daily use	39 (0.7)
Daily use	Non-daily use	26 (0.5)

Estimates presented in descending order as unweighted frequencies (percentages) among adults not lost to follow-up.

E-cigarette use patterns and 12-month sustained smoking abstinence

Table 3 presents results on 12-month cigarette smoking abstinence at wave 4 by vaping frequency patterns. A RR > 1.0 indicates exposure was associated with increased probability of smoking abstinence, while a RR < 1.0 indicates exposure was associated with decreased probability of smoking abstinence.

Compared to no current e-cigarette use at both waves, consistent non-daily e-cigarette use at both waves was associated with 72% lower probability of 12-month smoking abstinence at wave 4 (RR = 0.28, 95% CI = 0.11–0.75). In contrast, consistent daily e-cigarette use at both waves was associated with nearly four times the probability of 12-month smoking abstinence (RR = 3.82, 95% CI = 2.59–5.64) relative to no current e-cigarette use over follow-up. No current e-cigarette use at wave 2 followed by daily use at wave 3 was also positively associated with smoking abstinence at wave 4 (RR = 2.50, 95% CI = 1.66–3.77).

Daily e-cigarette use at wave 2 followed by no current e-cigarette use at wave 3 indicated a positive association (RR = 1.81, 95% CI = 0.89–3.65), and no current e-cigarette use at wave 2 followed by non-daily use at wave 3 indicated an inverse association with smoking abstinence (RR = 0.60, 95% CI = 0.34–1.07), although confidence intervals were consistent with a range of effects, including no association. Estimates for the remaining exposure patterns indicated no association with smoking abstinence (non-daily wave 2/non-use wave 3 RR = 0.90, 95% CI = 0.66–1.24) or were too imprecise to draw meaningful conclusions (daily wave 2/non-daily wave 3 RR = 1.65, 95% CI = 0.54–5.00; non-daily wave 2/daily wave 3 RR = 1.36, 95% CI = 0.55–3.35).

E-cigarette use patterns and substantial reduction in cigarette smoking

Compared to no current e-cigarette use over follow-up, non-daily use at both waves was associated with 28% lower probability of smoking reduction at wave 4 (RR = 0.72, 95% CI = 0.23–1.00) (Table 4). Daily e-cigarette use at either wave or both waves was positively associated with substantial reduction in cigarette smoking. For example, compared to no current e-cigarette use over follow-up, weighted RRs were 2.49 (95% CI = 2.12–2.93) for daily use at both waves and 2.03 (95% CI = 1.67–2.47) for no use at wave 2 and daily use at wave 3.

E-cigarette use patterns and tobacco product abstinence

Most vaping patterns were associated with a lower probability of abstinence from all tobacco products at wave 4, although estimates were imprecise with wide confidence intervals (Table 5). Daily e-cigarette use at wave 2 followed by no current e-cigarette use at wave 3 was the only exposure pattern positively associated with abstaining from all tobacco products (RR = 2.05, 95% CI = 0.95–4.42). However, given the wide confidence intervals, results for all tobacco-product abstinence should be interpreted with caution.

Sensitivity analyses

Restricting to participants with plans to quit smoking in the next year resulted in similar but slightly attenuated and more imprecise estimates, and we found no evidence of interaction between e-cigarette use frequency and intentions to quit smoking (interaction term *P*-value = 0.74, Supporting information, Table S3). The bias analysis suggested non-differential misclassification of e-cigarette exposure and smoking abstinence is expected, on average, to bias RRs towards the null (Supporting information, Table S4).

Secondary analysis

The multiplication of PATH wave 4 sample weights and inverse probability weights produced slightly stronger estimates for daily e-cigarette use patterns and slightly attenuated estimates for non-daily use patterns, but did not markedly alter conclusions (Supporting information, Table S5).

DISCUSSION

In this study of US adults who smoked cigarettes at baseline, participants who subsequently and consistently used e-cigarettes daily were more likely to report 12-month abstinence from cigarette smoking after 2 years than participants who reported no current e-cigarette use over follow-up. Participants who consistently used e-cigarettes non-daily were less likely to report cigarette smoking abstinence than participants who reported no current e-cigarette use. Results were robust to adjustment for time-dependent confounding, selection bias due to loss to follow-up and misclassification of e-cigarette use and

TABLE 2 Wave 1 covariates by e-cigarette use frequency at waves 2–3 among 5699 adults who smoke cigarettes and do not currently use e-cigarettes at wave 1

	Wave 2 e-cigarette use frequency			Wave 3 e-cigarette use frequency		
Covariates measured at wave 1	Non-use (*n* = 4842)	Non-daily (*n* = 693)	Daily (*n* = 164)	Non-use (*n* = 5077)	Non-daily (*n* = 414)	Daily (*n* = 208)
Female sex	50.8	51.8	45.1	50.7	53.5	46.6
Age, years						
18–34	39.0	51.4	48.2	39.4	51.7	51.4
35–54	38.3	36.6	40.2	38.8	32.4	35.1
≥ 55	22.7	12.0	11.6	21.8	15.9	13.5
Race/ethnicity						
Non-Hispanic black	17.5	12.0	6.1	17.2	13.5	4.8
Non-Hispanic white	62.8	68.3	76.2	62.8	69.8	78.4
Non-Hispanic Asian or other race	6.3	7.4	9.2	6.5	6.5	8.6
Hispanic	13.4	12.3	8.5	13.5	10.1	8.2
Sexual identity						
Lesbian, gay, bisexual+	8.0	11.7	11.0	8.0	11.8	13.0
Straight	92.1	88.3	89.0	92.0	88.2	87.0
Education						
< High school or equivalent	29.8	29.3	25.0	30.2	25.8	20.6
Some college or Associate's degree	59.5	61.2	67.7	59.0	66.2	71.2
≥ Bachelor's degree	10.7	9.5	7.3	10.8	8.0	8.2
Poverty status						
< 100% poverty level	42.0	49.5	37.2	42.5	48.5	38.9
≥ 100% poverty level	58.0	50.5	62.8	57.5	51.5	61.1
Duration regular cigarette smoking						
Never smoked regularly	7.0	4.6	4.3	6.8	6.0	3.9
< 18 years (median)	43.6	54.0	52.4	44.1	53.4	53.4
≥ 18 years (median)	49.4	41.4	43.3	49.1	40.6	42.8
Daily cigarette smoker	78.6	82.3	89.0	78.9	82.9	85.1
Smoking intensity, cigs per day						
1–10	52.9	50.4	45.7	52.4	55.3	46.6
11–19	15.8	17.3	14.0	16.0	16.0	13.0
≥ 20	31.3	32.3	40.2	31.6	28.7	40.4
Plans to quit smoking in the next year	59.3	58.3	59.2	59.4	58.0	56.3
Made a smoking quit attempt in past year	46.0	48.5	48.8	46.2	45.9	52.4
Nicotine dependence score (16-item), median (IQR)	53 (28–75)	59 (34–78)	66 (44–86)	53 (3–75)	56 (34–78)	63 (41–81)
Used NRT in past 12 months	10.2	11.5	9.8	10.1	11.8	15.4
Used prescription cessation aid in past 12 months	4.2	5.9	6.1	4.3	5.1	8.2
Perceived harm of e-cigarettes relative to cigarettes						
Less harmful	43.1	54.3	58.5	44.0	49.5	58.2
Equally or more harmful	56.9	45.7	41.5	56.0	50.5	41.8
Lives with a tobacco user	54.9	63.4	62.8	55.5	60.4	62.5
General view of tobacco among peers						
Positive	10.8	10.3	6.7	10.8	10.4	6.7
Neutral	31.5	38.2	36.6	31.9	37.4	36.1

(Continues)

TABLE 2 (Continued)

Covariates measured at wave 1	Wave 2 e-cigarette use frequency			Wave 3 e-cigarette use frequency		
	Non-use (*n* = 4842)	Non-daily (*n* = 693)	Daily (*n* = 164)	Non-use (*n* = 5077)	Non-daily (*n* = 414)	Daily (*n* = 208)
Negative	57.7	51.5	56.7	57.3	52.4	57.2
Diagnosis of tobacco-related disease	46.9	46.2	39.6	47.0	43.0	41.8
Past 30-day other tobacco product use	24.2	34.9	28.7	24.5	36.5	32.2
Past 30-day alcohol use	58.4	58.3	62.2	58.4	59.2	57.7
Past 30-day marijuana use	21.1	25.0	17.7	20.9	27.0	23.1
Past 30-day other drug use	11.2	15.2	15.9	11.4	16.2	13.5
Internalizing mental health problems						
Low	52.4	43.4	43.3	52.3	41.8	40.9
Medium	25.5	26.1	26.2	25.3	26.8	29.8
High	22.1	30.5	30.5	22.4	31.4	29.3
Externalizing mental health problems						
Low	59.9	51.2	49.4	59.7	48.3	50.5
Medium	24.2	26.3	33.5	24.3	29.2	26.4
High	15.9	22.5	17.1	16.0	22.5	23.1

Estimates presented as unweighted percentages except where indicated. NRT = nicotine replacement therapy; IQR = interquartile range.

TABLE 3 E-cigarette use and 12-month cigarette smoking abstinence at wave 4 among 5699 adults who smoke cigarettes and do not currently use e-cigarettes at wave 1: results from crude and marginal structural models

E-cigarette use wave 2	E-cigarette use wave 3	% Smoking Abstinent	Crude		MSM[a]	
			RR	95% CI	RR	95% CI
Any	Any	9.8	–	–	–	–
Non-use	Non-use	9.8	1.0	Ref	1.0	Ref
Non-daily use	Non-use	7.7	0.78	0.56–1.07	0.90	0.66–1.24
Non-use	Non-daily use	5.2	0.54	0.31–0.94	0.60	0.34–1.07
Non-daily use	Non-daily use	2.6	0.26	0.10–0.68	0.28	0.11–0.75
Non-use	Daily use	22.2	2.28	1.53–3.38	2.50	1.66–3.77
Daily use	Daily use	31.7	3.25	2.33–4.55	3.82	2.59–5.64
Daily use	Non-use	13.6	1.38	0.72–2.64	1.81	0.89–3.65
Non-daily use	Daily use	15.4	1.36	0.54–3.45	1.36	0.55–3.35
Daily use	Non-daily use	11.5	1.17	0.40–3.41	1.65	0.54–5.00

MSM = marginal structural model; RR = risk ratio; CI = confidence interval.
[a]Adjusted for wave 1 values of sexual identity, education, income, race/ethnicity, sex, age, smoking duration, smoking intensity, smoking frequency, quit attempt in past 12 months, plans to quit smoking in next 12 months, past 12-month use of nicotine replacement therapy or prescription cessation aid, past 30-day use of alcohol, marijuana or other drugs, past 30-day use of other tobacco products, high internalizing and/or externalizing mental health symptoms, perceived harm of e-cigarettes, lives with a tobacco user, peer opinion of tobacco and past 12-month diagnosis of tobacco-related disease. Additionally weighted by inverse probability and censoring weights adjusting for time-varying confounders and censoring.

smoking abstinence. Findings persisted among participants with plans to quit smoking at baseline.

This study contributes to prior findings in the literature of a positive association between daily vaping and cigarette smoking abstinence, but inverse associations between non-daily vaping and smoking abstinence [13, 14, 16, 47]. This study enhances the literature by examining vaping frequency at multiple time-points, which revealed important heterogeneity that would have been missed had exposure been operationalized as binary and limited to a single time-point. For example, the benefits of daily vaping on smoking abstinence were stronger for participants who used e-cigarettes daily at two waves compared to those who used e-cigarettes daily at one wave. Additionally, consistent non-daily e-cigarette use at two waves was the only vaping pattern associated with lower likelihood of cigarette

TABLE 4 E-cigarette use and substantial reduction in cigarette smoking by wave 4 among 5699 adults who smoke cigarettes and do not currently use e-cigarettes at wave 1: results from crude and marginal structural models

			Crude		MSM[a]	
E-cigarette use wave 2	E-cigarette use wave 3	% Substantial reduction[b]	RR	95% CI	RR	95% CI
Any	Any	29.8	–	–	–	–
Non-use	Non-use	28.7	1.0	Ref	1.0	Ref
Non-daily use	Non-use	28.5	1.01	0.87–1.16	1.0	0.87–1.16
Non-use	Non-daily use	29.4	1.04	0.85–1.28	1.01	0.82–1.25
Non-daily use	Non-daily use	19.8	0.66	0.48–0.92	0.72	0.52–1.00
Non-use	Daily use	58.2	2.02	1.68–2.43	2.03	1.67–2.47
Daily use	Daily use	72.5	2.52	2.18–2.91	2.49	2.12–2.93
Daily use	Non-use	40.7	1.42	1.04–1.93	1.42	1.01–2.00
Non-daily use	Daily use	40.5	1.40	0.91–2.16	1.43	0.91–2.24
Daily use	Non-daily use	38.5	1.34	0.82–2.18	1.69	1.07–2.65

MSM = marginal structural model; RR = risk ratio; CI = confidence interval.
[a]Adjusted for wave 1 values of sexual identity, education, income, race/ethnicity, sex, age, smoking duration, smoking intensity, smoking frequency, quit attempt in past 12-months, plans to quit smoking in next 12 months, past 12-month use of nicotine replacement therapy or prescription cessation aid, past 30-day use of alcohol, marijuana or other drugs, past 30-day use of other tobacco products, high internalizing and/or externalizing mental health symptoms, perceived harm of e-cigarettes, lives with a tobacco user, peer opinion of tobacco, past 12-month diagnosis of tobacco-related disease. Additionally weighted by inverse probability and censoring weights adjusting for time-varying confounders and censoring.
[b]Substantial reduction is ≥ 50% reduction in average cigarettes smoked/day between waves 1 and 4.

TABLE 5 E-cigarette use and 12-month abstinence from all tobacco products at wave 4 among 5699 adults who smoke cigarettes and do not currently use e-cigarettes at wave 1: results from crude and marginal structural models

			Crude		MSM[a]	
E-cigarette use wave 2	E-cigarette use wave 3	% Tobacco abstinent[b]	RR	95% CI	RR	95% CI
Any	Any	7.2	–	–	–	–
Non-use	Non-use	7.9	1.0	Ref	1.0	Ref
Non-daily use	Non-use	6.0	0.76	0.53–1.09	0.95	0.67–1.36
Non-use	Non-daily use	3.0	0.38	0.18–0.80	0.42	0.20–0.89
Non-daily use	Non-daily use	1.3	0.16	0.04–0.63	0.20	0.05–0.82
Non-use	Daily use	3.3	0.42	0.14–1.28	0.51	0.16–1.61
Daily use	Daily use	1.3	0.16	0.02–1.11	0.17	0.02–1.25
Daily use	Non-use	11.9	1.49	0.74–3.01	2.05	0.95–4.42
Non-daily use	Daily use	2.6	0.33	0.05–2.29	0.30	0.05–1.78
Daily use	Non-daily use	3.9	0.48	0.07–3.31	1.08	0.15–7.85

MSM = marginal structural model; RR = risk ratio; CI = confidence interval.
[a]Adjusted for wave 1 values of sexual identity, education, income, race/ethnicity, sex, age, smoking duration, smoking intensity, smoking frequency, quit attempt in past 12 months, plans to quit smoking in next 12 months, past 12-month use of NRT or prescription cessation aid, past 30-day use of alcohol, marijuana or other drugs, past 30-day use of other tobacco products, high internalizing and/or externalizing mental health symptoms, perceived harm of e-cigarettes, lives with a tobacco user, peer opinion of tobacco, past 12-month diagnosis of tobacco-related disease. Additionally weighted by inverse probability and censoring weights adjusting for time-varying confounders and censoring.
[b]Outcome includes no use of combustible cigarettes, e-cigarettes, cigars, pipe tobacco, hookah or smokeless tobacco in past 12 months at wave 4.

smoking reduction. Examination of longer-term patterns of e-cigarette use with smoking abstinence is relevant to a target trial framework [48], because exposure patterns have parallels to treatment regimens that could be evaluated in randomized trials if deemed feasible and ethical.

Our findings are consistent with a prior PATH study by Glasser *et al*. [19], who found that using e-cigarettes daily at each wave was associated with long-term cigarette smoking abstinence [19]. Our study expands upon prior findings by incorporating an additional data wave, a more comprehensive set of e-cigarette use patterns and

robust control for time-dependent confounding, selection bias and misclassification. The current study's findings coupled with prior literature [13, 14, 16, 19, 47] highlight that daily and non-daily vaping are distinct behaviors and should be treated separately in studies on tobacco-use.

There are potential explanations for the divergent relationships of daily and non-daily vaping with smoking abstinence. Daily vaping results in a greater dose of nicotine than non-daily use, which could reduce cigarette smoking frequency and cravings. Nicotine satiation would be particularly important in the context of acute situations that trigger smoking relapse (e.g. stressful events, alcohol use). Non-daily vaping might not provide the necessary nicotine dose to fully curb cigarette cravings and withdrawal. E-cigarettes' promise as a cessation aid lies predominantly in their use as a substitute for cigarettes. Most individuals who are established cigarette smokers tend to smoke cigarettes daily [49], and thus non-daily vaping is unlikely to result in behavioral changes needed to substitute for daily smoking. Dual use of e-cigarettes and cigarettes may increase nicotine dependence relative to no e-cigarette use, as individuals are exposed to nicotine from both products [17].

Differences between daily and non-daily vaping may also be the result of residual confounding. Non-daily vaping could reflect a phenotype of e-cigarette users whose objective is to use e-cigarettes recreationally or for convenience rather than to quit smoking cigarettes. People who vape daily may be more motivated to quit smoking than those who vape non-daily or not at all. Findings persisted after restricting to participants with plans to quit smoking cigarettes; however, there is probably heterogeneity in quitting motivation among those with plans to quit smoking, resulting in residual confounding. Some researchers believe that observational studies on e-cigarette use and cigarette smoking abstinence should be restricted to participants who report a quit attempt to ensure similar motivations across exposure groups [28]. Others believe that such an approach is too restrictive, and precludes the ability to make inferences about the impact of e-cigarettes at the population level [50]. To this point, we found no evidence that the association of daily vaping with smoking abstinence was moderated by motivations to quit smoking, suggesting potential benefits of daily vaping even among smokers who did not originally intend to quit smoking. Furthermore, motivation to quit could be a causal intermediate between e-cigarette use and smoking abstinence. Individuals may not have intentions to quit smoking prior to using e-cigarettes but could subsequently develop or increase quit motivations because of their experience with vaping.

Compared to no current e-cigarette use over follow-up, nearly all e-cigarette patterns were inversely associated with abstinence from all tobacco products (including e-cigarettes). These findings are driven by sustained e-cigarette use at wave 4. While certain patterns of e-cigarette use may aid smoking abstinence, vaping may contribute to longer-term nicotine dependence. Prior studies, including randomized controlled trials (RCTs), indicate that many people continue vaping after quitting cigarette smoking [9, 51]. In addition, there is some evidence that vaping among former cigarette smokers is associated with smoking relapse [52–54]. Daily vaping patterns were more rare in the current study population than non-daily patterns, and the reduction in quit rate among non-daily users was substantial. Therefore, the population benefits of daily vaping for smoking abstinence may be outweighed by the harms of non-daily patterns. Assessment of the net population effect on smoking must also account for the potential role of e-cigarettes in relapse among former smokers and in fostering new initiators of cigarettes among youth [55].

This study has some limitations. The prevalence of e-cigarette use was rare, resulting in imprecise estimates for some joint exposure patterns. Sparse data precluded the ability to evaluate effect measure modification by socio-demographic factors or smoking history/behaviors. Clinical relevance of the secondary outcome of ≥ 50% reduction in average cigarette consumption differs, depending on baseline smoking intensity and various smoking-related diseases. For example, smoking has a curvilinear relationship with cardiovascular disease, and reductions at lowest levels of exposure may be the most clinically relevant for lowering disease risk [56, 57]. However, reductions at higher levels of cigarette exposure have important implications for nicotine dependence and eventual cessation. There is substantial variation across e-cigarette devices in nicotine concentration and type (e.g. protonated versus free-base), which could contribute to non-differential exposure misclassification if vaping frequency is used as a proxy for actual nicotine exposure. There are other product characteristics important to the effect of vaping on smoking abstinence that were not examined, including intensity of use during vaping sessions, flavors and/or device type. Additionally, we did not include measures of reasons for using e-cigarettes in our analysis and all measures were self-reported by participants. Informed by an internal validation study [44], we assumed that the misclassification probabilities used in the bias analysis were non-differential. However, given the prospective design, misclassification of smoking abstinence might be differential with respect to e-cigarette exposure.

CONCLUSION

Results of this study revealed important heterogeneity in the association of e-cigarette use with cigarette smoking abstinence, smoking reduction and tobacco-product abstinence by longitudinal patterns of vaping frequency. After accounting for time-dependent confounding and selection bias, consistent daily vaping was associated with four times the probability of sustained 12-month smoking abstinence compared to no current e-cigarette use over 2 years of follow-up. Participants who reported consistent non-daily vaping at two waves were 72% less likely to achieve cigarette smoking abstinence than non-users. Most longitudinal patterns of e-cigarette use were associated with a lower likelihood of tobacco-product abstinence due to sustained vaping at the end of follow-up. Results highlight that daily and non-daily vaping are distinct behaviors with divergent relations with cigarette smoking abstinence. Data are informative to ongoing consideration of how to regulate e-cigarettes by the US Federal Drug Administration in the context of ongoing review of pre-market applications. Future studies and RCTs should compare the effect of varying regimens of e-cigarette use frequency and duration on tobacco

abstinence to determine patterns of use that aid in cigarette smoking cessation while preventing long-term vaping dependence.

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DECLARATION OF INTERESTS

None.

AUTHOR CONTRIBUTIONS

Alyssa Harlow: Conceptualization; formal analysis; methodology. **Andrew Stokes:** Conceptualization; formal analysis; methodology; supervision. **Daniel Brooks:** Conceptualization; formal analysis; methodology; supervision. **Emelia Benjamin:** Conceptualization; formal analysis; methodology; supervision. **Adam Leventhal:** Conceptualization; supervision. **Rob McConnell:** Conceptualization; supervision. **Jessica Barrington-Trimis:** Conceptualization; supervision. **Craig Ross:** Conceptualization; formal analysis; methodology; supervision.

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REFERENCES

1. Chan GCK, Stjepanović D, Lim C, Sun T, Shanmuga Anandan A, Connor JP, et al. A systematic review of randomized controlled trials and network meta-analysis of e-cigarettes for smoking cessation. Addict Behav. 2021;119:106912.
2. Kalkhoran S, Glantz SA. E-cigarettes and smoking cessation in real-world and clinical settings: a systematic review and meta-analysis. Lancet Respir Med. 2016;4:116–28.
3. Wang RJ, Bhadriraju S, Glantz SA. E-cigarette use and adult cigarette smoking cessation: a meta-analysis. Am J Public Health. 2020;111:230–46.
4. Bullen C, Howe C, Laugesen M, McRobbie H, Parag V, Williman J, et al. Electronic cigarettes for smoking cessation: a randomised controlled trial. Lancet. 2013;382:1629–37.
5. Caponnetto P, Campagna D, Cibella F, Morjaria JB, Caruso M, Russo C, et al. EffiCiency and safety of an eLectronic cigAreTte (ECLAT) as tobacco cigarettes substitute: a prospective 12-month randomized control design study. PLOS ONE. 2013;8:e66317.
6. Carpenter MJ, Heckman BW, Wahlquist AE, Wagener TL, Goniewicz ML, Gray KM, et al. A naturalistic, randomized pilot trial of E-cigarettes: uptake, exposure, and behavioral effects. Cancer Epidemiol Biomarkers Prev. 2017;26:1795–803.
7. Halpern SD, Harhay MO, Saulsgiver K, Brophy C, Troxel AB, Volpp KG. A pragmatic trial of E-cigarettes, incentives, and drugs for smoking cessation. N Engl J Med. 2018;378:2302–10.
8. Lee SH, Ahn SH, Cheong YS. Effect of electronic cigarettes on smoking reduction and cessation in Korean male smokers: a randomized controlled study. J Am Board Fam Med. 2019;32:567–74.
9. Hajek P, Phillips-Waller A, Przulj D, Pesola F, Myers Smith K, Bisal N et al. A randomized trial of E-cigarettes versus nicotine-replacement therapy. N Engl J Med 2019;380:629–637.
10. Eisenberg MJ, Hébert-Losier A, Windle SB, Greenspoon T, Brandys T, Fülöp T, et al. Effect of e-cigarettes plus counseling vs counseling alone on smoking cessation. JAMA. 2020;324:1844–54.
11. Walker N, Parag V, Verbiest M, Laking G, Laugesen M, Bullen C. Nicotine patches used in combination with e-cigarettes (with and without nicotine) for smoking cessation: a pragmatic, randomised trial. Lancet Respir Med. 2020;8:54064.
12. Villanti AC, Feirman SP, Niaura RS, Pearson JL, Glasser AM, Collins LK, et al. How do we determine the impact of e-cigarettes on cigarette smoking cessation or reduction? Review and recommendations for answering the research question with scientific rigor. Addiction. 2018;113:391–404.
13. Berry KM, Reynolds LM, Collins JM, Siegel MB, Fetterman JL, Hamburg NM, et al. E-cigarette initiation and associated changes in smoking cessation and reduction: the population assessment of tobacco and health study, 2013–2015. Tob Control. 2019;28:42–9.
14. Brose LS, Hitchman SC, Brown J, West R, McNeill A. Is the use of electronic cigarettes while smoking associated with smoking cessation attempts, cessation and reduced cigarette consumption? A survey with a 1-year follow-up. Addiction. 2015;110:1160–8.
15. Biener L, Hargraves JL. A longitudinal study of electronic cigarette use among a population-based sample of adult smokers: association with smoking cessation and motivation to quit. Nicotine Tob Res. 2015;17:127–33.
16. McDermott MS, East KA, Brose LS, McNeill A, Hitchman SC, Partos TR. The effectiveness of using e-cigarettes for quitting smoking compared to other cessation methods among adults in the United Kingdom. Addiction. 2021;116:2825–36.
17. Martínez Ú, Martínez-Loredo V, Simmons VN, Meltzer LR, Drobes DJ, Brandon KO, et al. How does smoking and nicotine dependence change after onset of vaping? A retrospective analysis of dual users. Nicotine Tob Res. 2020;22:764–70.
18. Morgan Snell L, Barnes AJ, Nicksic NE. A longitudinal analysis of nicotine dependence and transitions from dual use of cigarettes and electronic cigarettes: evidence from waves 1–3 of the path study. J Stud Alcohol Drugs. 2020;81:595–603.
19. Glasser A, Vojjala M, Cantrell J, Levy DT, Giovenco DP, Abrams D, et al. Patterns of e-cigarette use and subsequent cigarette smoking cessation over two years (2013/2014 to 2015/2016) in the population assessment of tobacco and health (PATH) study. Nicotine Tob Res. 2020;23:669–77.
20. Zhuang YL, Cummins SE, Sun JY, Zhu SH. Long-term E-cigarette use and smoking cessation: a longitudinal study with US population. Tob Control. 2016;25:i90–5.
21. Chaiton M, Diemert L, Cohen JE, Bondy SJ, Selby P, Philipneri A, et al. Estimating the number of quit attempts it takes to quit smoking successfully in a longitudinal cohort of smokers. BMJ Open. 2016;6:e011045.
22. Robins JM, Hernan MA, Brumback B. Marginal structural models and causal inference in epidemiology. Epidemiology. 2000;11(5):550–60.
23. Hernán MA, Robins JM. Causal Inference: What If. Published online 2020. Available at: https://www.hsph.harvard.edu/miguel-hernan/causal-inference-book/ Accessed 4 January 2022.
24. Hyland A, Ambrose BK, Conway KP, Borek N, Lambert E, Carusi C et al. Design and methods of the population assessment of tobacco and health (PATH) study. Tob Control 2017;26:371–378.

25. Harlow AF, Stokes A, Brooks DR. Socioeconomic and racial/ethnic differences in E-cigarette uptake among cigarette smokers: longitudinal analysis of the population assessment of tobacco and health (PATH) study. Nicotine Tob Res. 2019;21:1385–93.
26. Kasza KA, Edwards KC, Tang Z, Stanton CA, Sharma E, Halenar MJ, et al. Correlates of tobacco product cessation among youth and adults in the USA: findings from the PATH study waves 1–3 (2013–2016). Tob Control. 2020;29:s203–15.
27. Strong DR, Pearson J, Ehlke S, Kirchner T, Abrams D, Taylor K, et al. Indicators of dependence for different types of tobacco product users: descriptive findings from wave 1 (2013–2014) of the population assessment of tobacco and health (PATH) study. Drug Alcohol Depend. 2017;178:257–66.
28. Pierce JP, Messer K, Leas EC, Kealey S, White MM, Benmarhnia T. A source of bias in studies of E-cigarettes and smoking cessation. Nicotine Tob Res. 2019;22:861–2.
29. Riehm KE, Young AS, Feder KA, Krawczyk N, Tormohlen KN, Pacek LR, et al. Mental health problems and initiation of e-cigarette and combustible cigarette use. Pediatrics. 2019;144: e20182935.
30. Lê Cook B, Wayne GF, Kafali EN, Liu Z, Shu C, Flores M. Trends in smoking among adults with mental illness and association between mental health treatment and smoking cessation. JAMA. 2014;311: 172–82.
31. Hefner KR, Sollazzo A, Mullaney S, Coker KL, Sofuoglu M. E-cigarettes, alcohol use, and mental health: use and perceptions of e-cigarettes among college students, by alcohol use and mental health status. Addict Behav. 2019;91:12–20.
32. Kong G, Morean ME, Cavallo DA, Camenga DR, Krishnan-Sarin S. Reasons for electronic cigarette experimentation and discontinuation among adolescents and young adults. Nicotine Tob Res. 2015;17: 847–54.
33. Farkas AJ, Gilpin EA, Distefan JM, Pierce JP. The effects of household and workplace smoking restrictions on quitting behaviours. Tob Control. 1999;8:261–5.
34. Taylor R, Sidloff D, Sayers RD, Bown MJ, Saratzis A. Uptake and perceptions of E-cigarette use in vascular patients. J Smok Cessat. 2019;14:83–7.
35. Cole SR, Hernan MA. Constructing inverse probability weights for marginal structural models. Am J Epidemiol. 2008;168:656–64.
36. Robins JM, Greenland S, Hu FC. Estimation of the causal effect of a time-varying exposure on the marginal mean of a repeated binary outcome. J Am Stat Assoc. 1999;94:687–700.
37. Hernán MÁ, Brumback B, Robins JM. Marginal structural models to estimate the causal effect of zidovudine on the survival of HIV-positive men. Epidemiology. 2000;11:561–70.
38. Howe CJ, Cole SR, Lau B, Napravnik S, Eron JJ Jr. Selection bias due to loss to follow up in cohort studies. Epidemiology. 2016; 27(1):91.
39. Zou G. A modified Poisson regression approach to prospective studies with binary data. Am J Epidemiol. 2004;159:702–6.
40. Lash T, Fox M, Fink A. Applying Quantitative Bias Analysis to Epidemiologic Data New York, NY: Springer; 2009.
41. Wagenknecht LE, Burke GL, Perkins LL, Haley NJ, Friedman GD. Misclassification of smoking status in the CARDIA study: a comparison of self-report with serum cotinine levels. Am J Public Health. 1992;82:33–6.
42. Tourangeau R, Yan T, Sun H, Hyland A, Stanton CA. Population assessment of tobacco and health (PATH) reliability and validity study: selected reliability and validity estimates. Tob Control. 2019; 28:663–8.
43. Patrick DL, Cheadle A, Thompson DC, Diehr P, Koepsell T, Kinne S. The validity of self-reported smoking: a review and meta-analysis. Am J Public Health. 1994;84:1086–93.
44. Goniewicz ML, Smith DM. Are some E-cigarette users 'blowing smoke'?: assessing the accuracy of self-reported smoking abstinence in exclusive E-cigarette users. Nicotine Tob Res. 2019;21:699–700.
45. Lash TL, Fox MP, MacLehose RF, Maldonado G, McCandless LC, Greenland S. Good practices for quantitative bias analysis. Int J Epidemiol. 2014;43:1969–85.
46. Dugoff EH, Schuler M, Stuart EA. Generalizing observational study results: applying propensity score methods to complex surveys health services research. Health Serv Res. 2014;49:284–303.
47. Harlow AF, Fetterman JL, Ross CS, Robertson RM, Bhatnagar A, Benjamin EJ, et al. Association of device type, flavours and vaping behaviour with tobacco product transitions among adult electronic cigarette users in the USA. Tob Control. 2022;31:e10–7.
48. Hernán MA, Robins JM. Using big data to emulate a target trial when a randomized trial is not available. Am J Epidemiol. 2016;183:758–64.
49. US Department of Health and Human Services (USDHHS). The Health Consequences of Smoking—50 Years of Progress: A Report of the Surgeon General. Washington, DC: USDHHS; 2014.
50. Kalkhoran S, Chang Y, Rigotti NA. Response to: a source of bias in studies of E-cigarettes and smoking cessation. Nicotine Tob Res. 2020;22:863–3.
51. Benmarhnia T, Pierce JP, Leas E, White MM, Strong DR, Noble ML, et al. Can E-cigarettes and pharmaceutical AIDS increase smoking cessation and reduce cigarette consumption? Findings from a nationally representative cohort of American smokers. Am J Epidemiol. 2018;187:2397–404.
52. Dai H, Leventhal AM. Association of electronic cigarette vaping and subsequent smoking relapse among former smokers. Drug Alcohol Depend. 2019;199:10–7.
53. Everard CD, Silveira ML, Kimmel HL, Marshall D, Blanco C, Compton WM. Association of electronic nicotine delivery system use with cigarette smoking relapse among former smokers in the United States. JAMA Netw Open. 2020;3:e204813.
54. Pierce JP, Chen R, Kealey S, Leas EC, White MM, Stone MD, et al. Incidence of cigarette smoking relapse among individuals who switched to e-cigarettes or other tobacco products. JAMA Netw Open. 2021;4:e2128810.
55. Soneji S, Barrington-Trimis JL, Wills TA, Leventhal AM, Unger JB, Gibson LA, et al. Association between initial use of e-cigarettes and subsequent cigarette smoking among adolescents and young adults. JAMA Pediatr. 2017;171:788–97.
56. Lubin JH, Couper D, Lutsey PL, Woodward M, Yatsuya H, Huxley RR. Risk of cardiovascular disease from cumulative cigarette use and the impact of smoking intensity. Epidemiology. 2016;27: 395–404.
57. Lubin JH, Caporaso NE. Cigarette smoking and lung cancer: modeling total exposure and intensity. Cancer Epidemiol Biomarkers Prev. 2006;15:517–23.

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