

Original investigation

# The Application of a Decision-Theoretic Model to Estimate the Public Health Impact of Vaporized Nicotine Product Initiation in the United States

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## Abstract

**Introduction:** The public health impact of vaporized nicotine products (VNPs) such as e-cigarettes is unknown at this time. VNP uptake may encourage or deflect progression to cigarette smoking in those who would not have otherwise smoked, thereby undermining or accelerating reductions in smoking prevalence seen in recent years.

**Methods:** The public health impact of VNP use are modeled in terms of how it alters smoking patterns among those who would have otherwise smoked cigarettes and among those who would not have otherwise smoked cigarettes in the absence of VNPs. The model incorporates transitions from trial to established VNP use, transitions to exclusive VNP and dual use, and the effects of cessation at later ages. Public health impact on deaths and life years lost is estimated for a recent birth cohort incorporating evidence-informed parameter estimates.

**Results:** Based on current use patterns and conservative assumptions, we project a reduction of 21% in smoking-attributable deaths and of 20% in life years lost as a result of VNP use by the 1997 US birth cohort compared to a scenario without VNPs. In sensitivity analysis, health gains from VNP use are especially sensitive to VNP risks and VNP use rates among those likely to smoke cigarettes.

**Conclusions:** Under most plausible scenarios, VNP use generally has a positive public health impact. However, very high VNP use rates could result in net harms. More accurate projections of VNP impacts will require better longitudinal measures of transitions into and out of VNP, cigarette and dual use.

**Implications:** Previous models of VNP use do not incorporate whether youth and young adults initiating VNP would have been likely to have been a smoker in the absence of VNPs. This study

provides a decision-theoretic model of VNP use in a young cohort that incorporates tendencies toward smoking and shows that, under most plausible scenarios, VNP use yields public health gains. The model makes explicit the type of surveillance information needed to better estimate the effect of new products and thereby inform public policy.

## Introduction

The 2014 US Surgeon General's Report stated that the use of combustible tobacco, primarily cigarettes, is by far the dominant cause of the preventable deaths from tobacco use, but also noted that e-cigarettes, and variations in this class of noncombustible products, may help to speed the decline of lethal combustible tobacco use.<sup>1,2</sup> Vaporized nicotine products (VNPs), including e-cigarettes and heat-not-burn cigarettes, represent a new generation of nicotine delivery products. Although the long-term health risks have yet to be thoroughly characterized, VNPs are likely to be much safer than cigarettes<sup>3-5</sup> and are generally perceived by smokers as less risky than cigarettes.<sup>6-9</sup> In addition, some types of VNPs have been shown to deliver nicotine more efficiently than nicotine replacement products<sup>10-13</sup> and provide sensorimotor experiences similar to smoking.

The recent upsurge in VNP awareness and past 30-day use,<sup>14,15</sup> especially among youth, appears to have flattened.<sup>16-18</sup> Future uptake and use of VNPs will also be influenced by the regulatory context in which it is brought to market.<sup>19-23</sup> VNPs have been banned in some countries while being subject to few or no regulations in other countries.<sup>24</sup> With "deeming" regulation,<sup>25</sup> the US Food and Drug Administration (FDA) is now confronting the challenge of how to regulate VNPs in ways that would be beneficial to public health, while recognizing that "sufficient data about e-cigarettes to determine (VNPs) effect on the public health"<sup>25</sup> are not yet available.

If used instead of smoking cigarettes, VNPs provide the potential to reduce harm and thereby improve population health.<sup>1,26</sup> However, VNPs have the potential to increase population-level harm if youth who would not have otherwise smoked become cigarette smokers as a direct consequence of using VNPs<sup>27-32</sup> (ie, a hypothesized gateway) or if current smokers who would otherwise have quit smoking cigarettes instead delay or fail to quit.<sup>33,34</sup>

In the absence of the requisite data, modeling can provide a structure to analyze the public health impact under different assumptions about how VNPs might be used. This paper presents a decision-theoretic model of the public health impact of VNP use in the United States. Unlike previous models of e-cigarette use,<sup>34-36</sup> our model is cohort- rather than age-based. While cohorts may differ in terms of awareness, perceived risks, products available (eg, flavorings, ability to satisfy nicotine cravings), and user characteristics (eg, early vs. late adopters, high vs. low income), we model the potential impact of VNP initiation on VNP and cigarette use using a recent cohort of young people.

The model improves on previous work by explicitly modeling the decisions that individuals make at each age regarding VNP use and comparing that use to a no-VNP use scenario based on an age-period-cohort analysis.<sup>37</sup> We project the likely future impact of VNPs based on the best available evidence. Sensitivity analysis is used to discern the trade-off between harm-reducing and harm-increasing effects of VNP use on net public health and to identify the specific parameters that contribute to the net effect of VNPs. Our analysis also identifies the kind of data that are needed to better evaluate the public health impact of VNP use.

## Methods

The analysis is confined to patterns of VNP and cigarette use, since cigarette smoking is the dominant threat to public health.<sup>1,2</sup> Using data on smoking rates prior to when VNPs were introduced, we describe a hypothetical "No-VNP scenario" as the projection of future smoking rates in the absence of VNPs. We then consider a hypothetical, data-informed VNP use scenario where patterns of VNP use and associated cigarette smoking interact to influence health outcomes. Public health implications are derived in terms of the change in smoking-related mortality and life years gained or lost between the two scenarios.

### The "No-VNP Scenario"

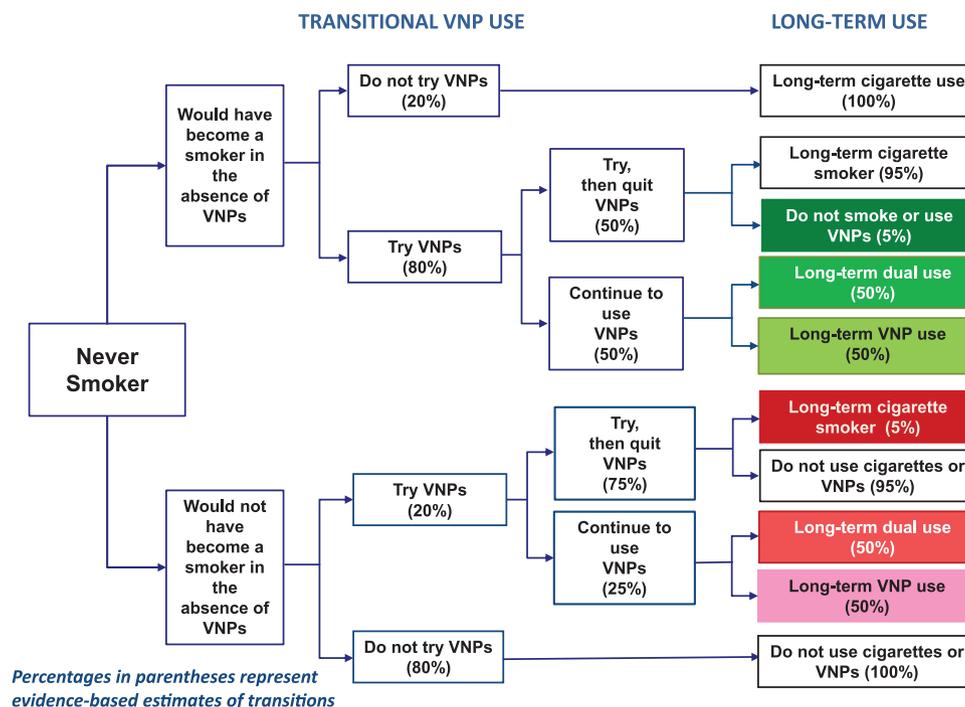
To estimate smoking rates in the absence of VNP use, we analyze a cohort of current, former, and never smokers in the United States using data through 2012. The data were developed<sup>38</sup> by applying an age-period-cohort statistical technique<sup>37</sup> to National Health Interview Surveys (NHIS) from 1965–2012 while correcting for bias due to higher mortality among smokers. Since sustained VNP use was still low in 2012,<sup>14</sup> the NHIS data are used to approximate cigarette smoking trends prior to VNPs.

A representative cohort of individuals aged 15 years in 2012 (born in 1997) was chosen, since most initiation into smoking takes place beginning at age 15.<sup>39</sup> Projected initiation and cessation rates are used to calculate current, former, and never smoker prevalence through the year 2083 in the absence of VNPs. Never smokers become current smokers reflecting their initiation at each age, with some percentage of smokers who are alive at a given age becoming former smokers as a result of cessation. Cessation is measured as the percent quit for 2 years to approximate net cessation, taking into account relapse rates.<sup>38</sup>

### VNP Scenarios

The VNP model includes (1) established use of VNPs alone, (2) cigarettes alone, (3) dual use of VNPs and cigarettes, and (4) nonuse of either. "Established use" is conceptualized as long enough for measurable harms to accumulate, which typically requires years of use for cigarettes.<sup>40</sup> Established dual user refers to frequent use of both products (eg, at least weekly), since occasional use of one (eg, once in the past month) and regular use of the other is unlikely to materially affect risk profiles. While established use of VNPs and cigarettes is used to determine health outcomes, short-term ("trial") use of VNPs is incorporated as a direct pathway into established use, since most estimates of VNP use in the literature (eg use at least once in the past 30 days) are likely to reflect primarily short-term rather than long-term use.<sup>41,42</sup>

Potential transitions and public health impacts are distinguished relative to the No-VNP scenario of otherwise smokers (ie, those who would have become smokers without VNPs being on the market) and otherwise nonsmokers. As shown in [Figure 1](#), green endpoints indicate harm-reducing and red endpoints indicating harm-increasing endpoints. VNP use is harm-reducing for those who would have



**Figure 1.** Transitional vaporized nicotine product (VNP) use. Percentages in parentheses represent evidence-based estimates of transitions.

otherwise smoked and instead become exclusive or dual VNP users, or use and then quit VNPs without smoking. Harm is increased for those who would not have otherwise smoked cigarettes and transition to long-term cigarette use as a direct result of VNP use or transition to established exclusive VNP cigarette or dual use.

To distinguish public health implications, we differentiate transitions by those who would have otherwise initiated smoking at each age from those who would have remained nonsmokers. To avoid double counting of those individuals who would not have otherwise have smoked, we use the smoking prevalence at the peak age (age 25 with smoking prevalence 19%) in the No-VNP model to determine the population of nonsmokers who engage in trial use.

We assume that individuals progress from trial use into a single state of exclusive cigarette, exclusive VNP, dual, or no use. While this assumption is made for model tractability, transitions to and from smoking abstinence are rarely smooth; many experiment with a product and do not transition to established use, or have periods of experimentation alternating with periods of use before transitioning to a stable state.<sup>43,44</sup> The model could be extended to incorporate multiple transitions, but the resultant use rates are critical, rather than the details of how they occur. After age 25, cessation of exclusive cigarette, VNP, and dual use is assumed to occur at the rate of smoking cessation under the No-VNP scenario. However, we consider cases where cessation rates of dual and/or exclusive smokers increase (eg, due to VNP availability) or decrease.

Assumptions and their justifications are shown in Supplementary Table 1.

### “Base Case” VNP Scenario

The transitions in Figure 1 under the VNP scenario were developed using estimates from recent literature. We chose estimates that imply more conservative effects (ie, outcomes that yield less harm reduction), with the percent following each path shown in Figure 1 and described in Supplementary Table 2.

In a large 2014 nationally representative US sample of 17- to 18-year-old students,<sup>42</sup> 7% of those who never smoked had used an e-cigarette in the last month compared to about 50% of those who had regularly or occasionally smoked. In other US studies, the odds of current youth e-cigarette use by smokers was 7.9 compared to nonsmokers,<sup>45</sup> young adult current e-cigarette use was 31% among smokers compared to 10% among former smokers and 2% among never smokers,<sup>46</sup> and the odds of college student e-cigarette use relative to never smokers was 3.1 for ever smokers and 6.6 for current smokers.<sup>47</sup> VNP users have also been found to be those who are more susceptible to smoking.<sup>48-50</sup> Based on the combined use of youth and young adults, we estimate that 80% of otherwise smokers try VNPs and 20% of otherwise nonsmokers try VNPs, a 4:1 ratio.

Of 17- to 18-year-old past month e-cigarette users,<sup>42</sup> 32% of never smokers used e-cigarettes 6 or more days compared to 50% among those who occasionally or regularly smoked cigarettes. Similar results were found in a recent study of 17–18 year olds<sup>51</sup> and studies of adults.<sup>46,52,53</sup> While these studies do not distinguish otherwise smokers from otherwise nonsmokers, VNP users have been found to have similar profiles to cigarette smokers (eg, common risk behaviors<sup>47,54,55</sup> and higher rates of executive function deficits, parental and peer cigarette use<sup>56</sup>). Based on these studies, particularly the large scale 2014 sample of 17–18 year olds,<sup>42</sup> we estimate that 50% of smokers and 25% of nonsmokers who try VNPs progress to established use, implying that 40% (80% \* 50%) of all smokers and 5% (20% \* 25%) of nonsmokers become established VNP users, an 8:1 ratio.

Of 17–18 year olds, 24% of those currently smoking at least half a pack per day used VNPs 6 or more days compared to 31% of never smokers.<sup>42</sup> Another study<sup>54</sup> obtained a prevalence of 17% for exclusive VNP use compared to 12% for dual use, with both group exhibiting similar risk factors to exclusive cigarette users. Among adults who used VNPs in the last month, one study<sup>52</sup> found that 41% of current, but 51% of former, smokers were regular users, and

another<sup>17</sup> found close to 70% of recent former smokers were daily users compared to about 23% of current smokers and less than 1% of never smokers. Since none of the studies indicated that more than 50% of regular users were current smokers and the studies do not provide evidence to explicitly distinguish otherwise smokers from otherwise nonsmokers, we estimate that established VNP users are split between dual users and exclusive VNP users for both otherwise smokers and otherwise nonsmokers.

In the absence of evidence on VNP users who do not continue to established use, we estimate that 5% of otherwise nonsmokers become smokers and 5% of otherwise smokers become nonsmokers. Among those not trying VNPs, we assume no change in status among otherwise smokers and nonsmokers.

We consider variations for each of the potential transitions by otherwise smokers and otherwise nonsmokers in the VNP base case to gauge sensitivity. Holding all other parameters constant, we consider trial use rates among otherwise smokers to vary between 0% and 100%. We then individually consider variations for trial use rates among otherwise smokers holding all other parameters constant. Similarly, we consider transitions from trial to established use and transitions from established use to dual use for both otherwise nonsmokers and otherwise smokers.

## Health Outcomes

All-cause cohort life tables by age, cohort, and sex were calculated by cigarette smoking status (never, former, and current) using mortality relative risk estimates by sex and smoking status derived from the American Cancer Society Cancer Prevention Studies I and II partitioned by smoking status.<sup>38</sup> Excess risk was calculated by age and gender as the mortality rate for smokers—mortality rate for never smokers and similarly for former smokers.

Although the long-term implications are not yet known and will likely vary by product,<sup>3,57–59</sup> VNPs contain substantially lower levels of toxic substances<sup>59–62</sup> and are thus likely to be much lower risk than cigarettes.<sup>3–5</sup> A multidecision analysis estimated that exclusive VNP use is associated with 5% of the risks of exclusive cigarette use,<sup>5</sup> similar to the risks of low-nitrosamine smokeless tobacco (snus) use.<sup>63</sup> Since lung cancer and chronic obstructive pulmonary disease risk are sensitive to smoking duration and intensity,<sup>64,65</sup> dual users may have lower mortality risk than exclusive cigarette smokers if VNP use delays smoking initiation or reduces the average quantity smoked. While some studies of VNP use report reductions in cigarette use of more than 50%,<sup>9,66–70</sup> others indicate smaller reductions, especially among nondaily VNP users.<sup>71,72</sup> A review found 75%–80% lower cigarette consumption among dual cigarette and snus users than among exclusive smokers.<sup>73</sup>

We estimate that among those who are exclusive VNP users the excess health risk is 5% whereas among dual users of cigarettes and VNPs the excess risk is 70% of cigarette only users. We also consider risks at 2.5% and 50% (low), 10% and 85% (medium), and 25% and 100% (high) for exclusive and dual use, respectively. Excess risks for former dual and exclusive VNP users are assumed to decline by the same percentages as applied to the difference in risk between current and former smokers.

## Calculation of Lives and Life Years Lost

For the No-VNP scenario, the number of smoking-attributable deaths (SADs) is calculated for current and former smokers for each age in the 1997 cohort as the product of excess risks and the

corresponding population (projected US population<sup>74</sup> multiplied by the prevalence rate). The number of life years lost (LYL) at each age is estimated as the product of number of premature deaths and the expected years of life remaining for a never smoker. For each VNP scenario, SADs and LYL are calculated for current and former exclusive smokers, exclusive VNP users and dual users, at each age and then summed. The public health impact of VNP use is measured by the difference in SADs and LYL under the No-VNP and VNP scenario.

## Results

### No-VNP Versus VNP Scenarios

**Table 1** contains male and female smoking and VNP prevalence, smoking-attributable deaths and LYL under the No-VNP scenario and the evidence-informed VNP scenarios. The 1997 cohort at age 15 years in 2012 includes 2 118 400 males and 2 025 700 females (Supplementary Table 3).

Under the No-VNP scenario, male smoking prevalence at age 15 is 4.6% increasing to 20.4% at age 25, and declining to 5.6% at age 65, while female prevalence at age 15 is 2.7% increasing to 14.3% at age 25, and declining to 3.5% at age 65. A cumulative total of 79 300 SADs and 1 539 200 LYL are estimated for males and 21 600 SADs and 419 100 LYL for females, a total of 100 900 deaths and 1 958 300 LYL from smoking in the 1997 birth cohort.

Under the VNP base case scenario, exclusive smoking is reduced by age 25 to 12.4% for males and 8.9% for females, but is offset through increased dual (5.9% males and 4.9% for females) and exclusive VNP dual (male 5.9% and female 4.9%) use. The cumulative loss through age 85 is 61 000 SADs and 1 208 000 LYL for males and 17 500 SADs and 350 000 LYL for females. Compared to the No-VNP scenario, a net public health gain of 23% fewer male and 19% fewer female SADs and 21.5% fewer male and 16.6% fewer female LYLs are projected. With low VNP mortality risks, 28% fewer SADs and 26% fewer LYL are projected. The gains decrease to 15% fewer SADs and 14% fewer LYL with medium risks and 6% fewer SADs and 5% fewer LYL with high risks.

If cessation rates are reduced by 10% in later years (**Table 1** and Supplementary Table 4), male LYL increase by 2475 (–0.20% lower than with no effect on cessation for the evidence-informed risk estimates) if only smokers are affected and by 3181 (0.26%) if dual users are also affected. A 10% cessation increase yields a male life year gain of 2042 (0.17) if only affecting smokers and 2769 (0.23%) if also affecting dual users. Changes for females are slightly larger, as much as 0.40%.

### Sensitivity Analysis

The sensitivity of results is assessed by changing individual parameters while holding constant other parameters at the base VNP levels. Parameter sensitivity is gauged by the variability (from 0% to 100%) in combined male and female LYL as that parameter changes. Gender variations are shown in Supplementary Figures 1–3 and in Supplementary Table 5.

Holding constant the other parameters (including use by otherwise nonsmokers and rates of exclusive and dual VNP use and established use rates), the public health impact on otherwise smokers (**Figure 2**) for trial use increased from 93 000 LYL at 0% use to a net gain of 525 000 life years gained at 100% use, with break-even where VNP trial use equals 15%. At less than 15% trial use

**Table 1.** Male and Female Smoking and Vaporized Nicotine Product (VNP) Prevalence, Smoking-attributable Deaths, and Life Years Lost, Under No-VNP and Base VNP Scenario, By Risk Levels and With Cessation Rate Effects

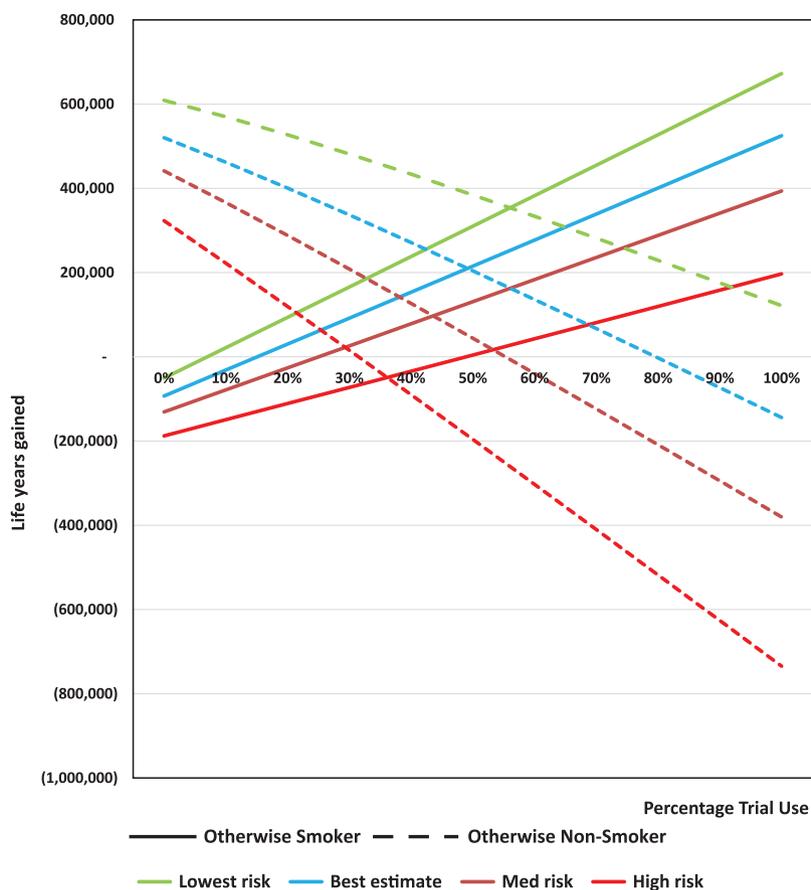
		Age	15 years	25 years	45 years	65 years	85 years	Cumulative: Age 15–85 years	Reduced LYL and SADs <sup>a</sup>	% Gain <sup>a</sup>
<b>Male</b>										
No-VNP scenario	Prevalence	Smoker	4.6%	20.4%	12.7%	5.6%	1.1%			
	SADs		—	—	581	2116	2816	79 322		
	LYL		—	—	23 573	46 335	16 706	1 539 242		
VNP best estimate risk	Prevalence	Smoker	2.8%	12.4%	7.7%	3.4%	0.6%			
		VNP	1.3%	5.9%	3.7%	1.6%	0.3%			
		Dual	1.3%	5.9%	3.7%	1.6%	0.3%			
	SADs		—	—	480	1653	2041	61 058	18 264	23.0%
	LYL		—	—	19 465	36 184	12 108	1 208 000	331 242	21.5%
Variation in levels of VNP and dual risks										
Low risk	SADs		—	—	442	1522	1879	56 213	23 109	29.1%
	LYL		—	—	17 921	33 313	11 147	1 112 151	427 091	27.7%
Medium risk	SADs		—	—	514	1769	2185	65 365	13 958	17.6%
	LYL		—	—	20 838	38 736	12 962	1 293 200	246 042	16.0%
High risk	SADs		—	—	565	1944	2401	71 824	7498	9.5%
	LYL		—	—	22 898	42 564	14 243	1 421 000	118 242	7.7%
Changes in cessation rate with best estimate risks										
10% Decrease smoker only	SADs		—	—	481	1656	2046	61 187	18 135	22.9%
	LYL		—	—	19 507	36 255	12 138	1 210 475	328 766	21.4%
10% Decrease smoker and dual user	SADs		—	—	481	1657	2047	61 221	18 101	22.8%
	LYL		—	—	19 521	36 275	12 143	1 211 182	328 060	21.3%
10% Increase Smoker only	SADs		—	—	479	1650	2039	60 962	18 360	23.1%
	LYL		—	—	19 425	36 124	12 095	1 205 958	333 284	21.7%
10% Increase smoker and dual user	SADs		—	—	479	1649	2038	60 928	18 395	23.2%
	LYL		—	—	19 410	36 103	12 090	1 205 231	334 011	21.7%
<b>Female</b>										
No-VNP scenario	Prevalence	Smoker	2.7%	14.3%	8.8%	3.5%	0.5%			
	SADs		—	—	66	609	987	21 609		
	LYL		—	—	2844	14 635	6955	419 076		
VNP best estimate risk	Prevalence	Smoker	1.7%	8.9%	5.5%	2.2%	0.3%			
		VNP	0.9%	4.9%	3.0%	1.2%	0.2%			
		Dual	0.9%	4.9%	3.0%	1.2%	0.2%			
	SADs		—	—	58	517	726	17 561	4048	18.7%
	LYL		—	—	2502	12 432	5111	349 551	69 525	16.6%
Variation in levels of VNP and dual risks										
Low risk	SADs		—	—	53	472	662	16 023	5587	25.9%
	LYL		—	—	2283	11 343	4663	318 929	100 147	23.9%
Medium risk	SADs		—	—	62	557	782	18 929	2681	12.4%
	LYL		—	—	2696	13 401	5508	376 771	42 306	10.1%
High risk	SADs		—	—	69	618	867	20 980	629	2.9%
	LYL		—	—	2989	14 853	6105	417 600	1476	0.4%
Changes in cessation rate with best estimate risks										
10% Decrease smoker only	SADs		—	—	58	519	728	17 616	3994	18.4%
	LYL		—	—	2507	12471	5128	350 585	68 491	16.1%
10% Decrease smoker and dual user	SADs		—	—	58	519	729	17 634	3975	18.3%
	LYL		—	—	2509	12 485	5132	350 950	68 126	16.0%
10% Increase smoker only	SADs		—	—	58	516	724	17 516	4093	18.9%
	LYL		—	—	2497	12 397	5101	348 638	70 438	16.6%
10% Increase smoker and dual user	SADs		—	—	58	515	724	17 499	4111	19.0%
	LYL		—	—	2495	12 383	5097	348 291	70 786	16.7%

LYL = life years lost; SADs = smoking-attributable deaths.

<sup>a</sup>Reduced life years lost and reduced SADs are measured in terms of the difference from the no-VNP scenario.

by otherwise smokers, the LYL due to use by otherwise nonsmokers (held constant at the evidence-informed level) dominates. For otherwise nonsmokers, the public health impact declines from 519 000 life years gained to 134 000 LYL, with breakeven when VNP trial use reaches 80%. Thus, 80% of otherwise nonsmokers would

be required to seriously experiment with VNPs for overall public health harm with our best estimate of risks, and 30% of otherwise nonsmokers would be required to seriously experiment with VNPs for the high level of risks. Notably, as gauged by absolute value of their slopes between 0% and 100%, the public health impact is less



**Figure 2.** Vaporized nicotine product (VNP) trial use sensitivity analysis among never smokers. Sensitivity analysis is conducted holding other use parameters constant, including trial and dual use.

sensitive among otherwise nonsmokers than otherwise smokers at the lower levels of risk, but becomes less sensitive at the higher levels of VNP risk, as expected.

Increasing established use (Figure 3) also increases the gain among otherwise smokers while decreasing the gain among otherwise nonsmokers. Holding constant the other parameters, LYL is 10 000 at 0% established use by those otherwise smokers who try VNPs and reaches over 800 000 life years gained at 100% established use. Breakeven from LYL is at or near zero at the two lower levels of VNP risk, and at 10% for the medium and 25% at the high level of VNP risk. The tipping point with for otherwise nonsmokers is at or near 100% for the three lower levels of risk, and at 45% for the high risk level. The sensitivity to use levels is greater among otherwise smokers than among otherwise nonsmokers at lower risks, but reverses at higher risks.

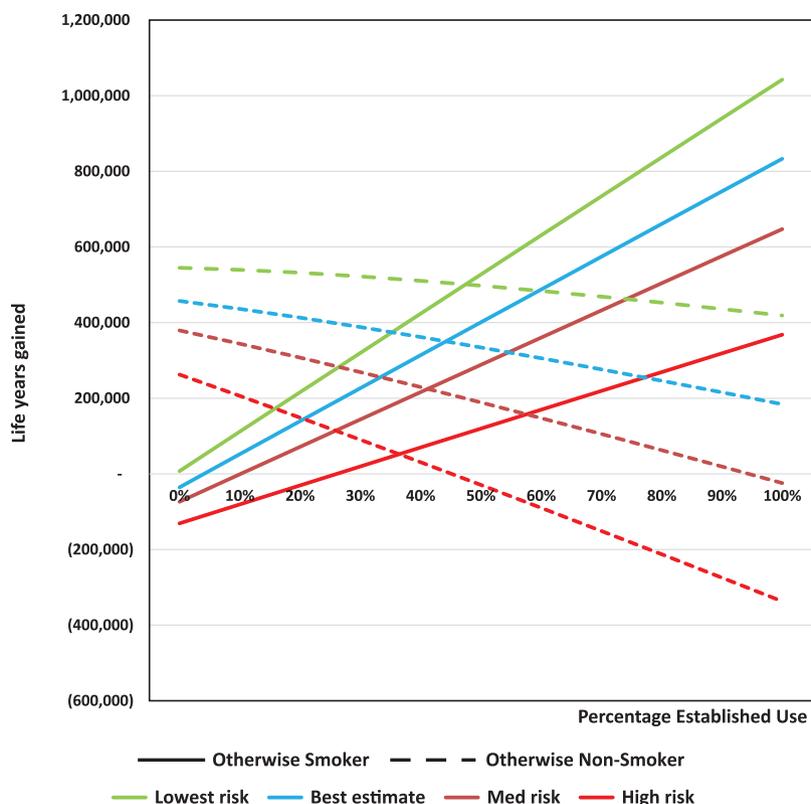
Figure 4 shows that the LYL as dual use among established users increases from 0% to 100% while exclusive VNP use concurrently declines from 100% to 0%. As expected, increasing dual use leads to decreasing health gains from VNP use among both otherwise smokers and otherwise nonsmokers. The sensitivity among otherwise smokers as measured by the absolute value of the slope increases at higher risk levels, but changes little for otherwise nonsmokers. Among otherwise smokers, the tipping point to LYL is slightly less than 100% dual use (ie, no exclusive VNP use) for medium risk and at 75% for high risk. Among otherwise nonsmokers with all other levels of use held constant, public harm (negative life years gained)

is projected as dual use increases above 50% for the highest level of risk.

## Discussion

The VNP decision-theoretic model of initiation shows that, while vaping leads to some VNP use and smoking by those who would not have otherwise smoked, the negative public health impact may be offset by the benefits from greater use of VNPs among otherwise smokers who smoke less or not at all. Under evidence-based estimates based on current use patterns, we estimate that 21% of SADs and 20% of LYL would be averted as a result of VNP use for a single cohort. Moreover, public health gains are estimated over a wide range of plausible parameters and use rates. A large proportion of VNP initiation leading directly to more cigarette smoking by otherwise never smokers or an increase in the magnitude of harms from VNPs relative to cigarettes (or both) would be required before a tipping point is reached where harms begin to exceed benefits at the population level.

While the high VNP risk estimates imply less health gains from VNP use, VNPs are likely to be increasingly regulated for quality control, thereby reducing levels and variability in risks. We expect that the highest risk estimates that we modeled are unlikely. Regulations that reduce risks and accurately communicate ingredients and nicotine levels in VNPs can be expected to encourage switching to exclusive VNP use and thus reduce the harms associated with smoking. A regulatory balance is needed that protects the public from



**Figure 3.** Vaporized nicotine product (VNP) established use sensitivity analysis among never smokers. Sensitivity analysis is conducted holding other use parameters constant, including established and dual use.

avoidable harms while at the same time allowing for innovation in VNP that encourage the substitution of VNP for cigarettes.

Sensitivity analysis also showed that those with a higher propensity to smoke (“otherwise smokers”) are especially sensitive to VNP use rates, suggesting the need for stronger tobacco control efforts to discourage combustible use (eg, increase cigarette and cigar taxes, higher minimum purchase age laws,<sup>75</sup> targeting combustible use in prevention and cessation media campaigns, and stricter smoke-free air laws). These policies would not only discourage transitions to combustible use but encourage switching to exclusive VNP use by those who otherwise cannot or will not quit combustible product use at early ages. Nevertheless, policies are needed to discourage youth initiation, especially by otherwise nonsmokers into any tobacco or VNP use. These policies may include higher and better enforced minimum purchase age laws marketing restrictions and VNP taxes although proportional to harms of combustible use.<sup>75,76</sup>

Because of our focus on initiation and the recent cohort analyzed, the effects of VNP through later cessation, as expected, played a minimal role. By assumption, the transitions to VNP use occurred largely at earlier ages. For older cohorts that have initiated smoking before VNP were more widely used (eg, those aged 26 or older in 2012), VNP can potentially play a key role in encouraging smoking cessation; smokers who began smoking before VNP were readily available can benefit from switching to exclusive VNP use, especially at younger ages when cessation from cigarettes is typically low<sup>77</sup> and health benefits from cessation are high.<sup>78</sup>

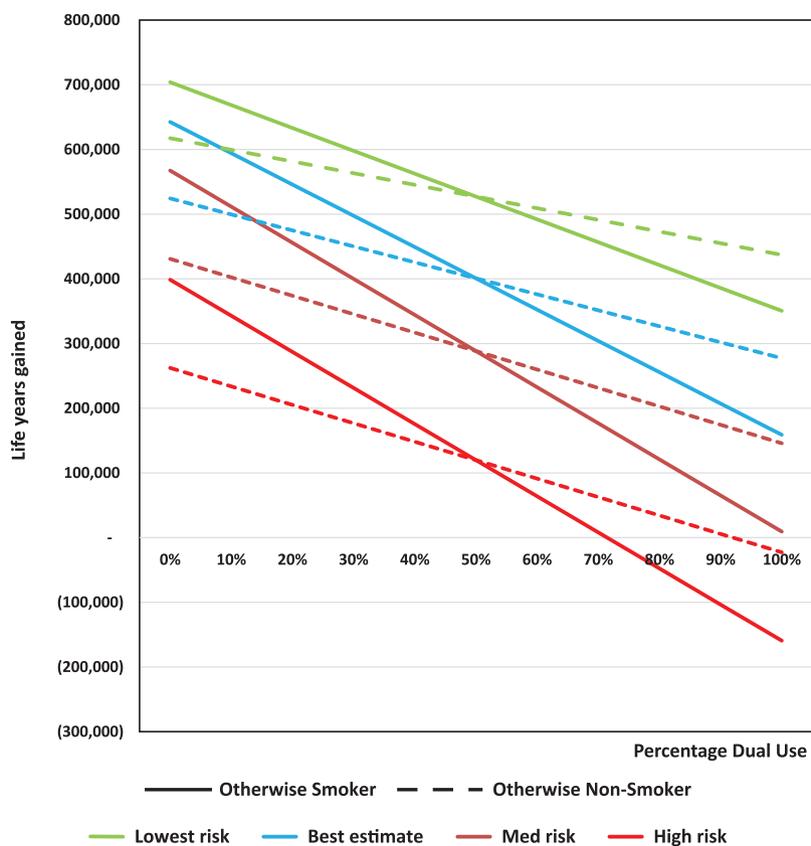
Thus, a careful balance must be struck that maximizes potential benefits by encouraging VNP use among otherwise smokers while minimizing harms to those who would not have otherwise smoked

or who would have otherwise quit.<sup>1,2</sup> Given the disproportionate power of the tobacco industry in this market space, there is a strong need for clear and accurate education of the public about the relative harms of each class of products and what behaviors substantially reduce or eliminate those harms. Ongoing longitudinal postmarket surveillance is needed to detect early warning signs of unintended negative consequences especially at early ages.

The decision-theoretic model has several limitations. As with all models of this nature, the projected public health gains depend on assumptions and the parameter estimates chosen for the model. While public health gains depend on the parameters chosen for the model, our aim was to apply conservative estimates of use by otherwise smokers and otherwise nonsmokers. For example, a recent meta-analysis<sup>79</sup> found that current smokers had 15 times the odds of current e-cigarette use compared to nonsmokers, increasing to 39 times the odds for adolescents. We also estimated that 25% of otherwise nonsmokers progressed to established VNP use and 50% of those became dual users, both of which we expect are overly pessimistic estimates.<sup>80</sup>

The empirical estimates we have used to inform the model are from the early stages in the use of these products. It is likely that current estimates underestimate eventual use, but short of a consensus estimate of likely trends, we have taken the conservative approach of using the most current data. If usage declines, then the estimates of benefits will also decline.

We considered cessation by the 1989 cohort, but we limited our analysis to changes in cessation at later ages among dual and exclusive VNP users. Similar effects may be expected among cigarette smokers, suggesting that the estimated gains from VNP use may be understated. In addition, we have assumed a single transition to



**Figure 4.** Dual versus exclusive vaporized nicotine product (VNP) use sensitivity analysis among never smokers. Sensitivity analysis is conducted holding other use parameters constant, including trial and established use.

the final state. In measuring transitions to established use, it will be important for future studies to allow for the possibility that transitions, for example, from dual use to exclusive VNP use, may occur later in life.

The use of other tobacco products, such as cigars, water pipe, and smokeless tobacco, may also influence the patterns of VNP and cigarette use. Cigar, smokeless tobacco, and hookah use has increased in recent years,<sup>2</sup> especially among youth.<sup>16,18</sup> However, unless long-term use of these products markedly increases, we expect that inclusion of these tobacco products is unlikely to substantially change the results.

Results of our model should not be strictly compared to others that address e-cigarette use.<sup>34–36</sup> The various models that have been developed so far differ in their structure, population focus, and modeling methods. Whereas we focused on a specific age cohort, other models<sup>34,36</sup> have attempted to generalize to the entire US population. In addition, we model a process dependent on whether the individual is an otherwise smoker or otherwise nonsmoker, while other models have focused on behavioral transitions between tobacco product use states. Nevertheless, our results are broadly consistent with the models of Cobb et al.<sup>35</sup> and Cherng et al.<sup>36</sup> The differences from Kalkhoran and Glantz model<sup>34</sup> appear to result from their higher rates of initiation into smoking implied by VNP use and higher levels of VNP risks.

The model highlights which transitions will need to be studied more closely to more accurately determine the effects of VNPs and evaluate policies affecting VNPs. The initial branch in Figure 1 leads to hypothetical states which cannot be observed and are inferred from past smoking patterns. While some studies have examined the relationship of VNP use to smoking,<sup>45,81,82</sup> these have been

cross-sectional or relatively short-term and alternative explanations, such as shared common vulnerabilities and other confounders, cannot be omitted.<sup>31,83,84</sup> Needed are better measures of trial use taking into account variations in the cigarette-oriented and VNP-oriented policies that are in place.

In conclusion, our analysis suggests the likelihood of public health gains due to VNP use at early ages under most plausible scenarios, and sensitivity analysis provides an indication of tipping points where harms will exceed benefits. The possibility of public health harms exceeding benefits must be carefully monitored via national longitudinal surveillance in order to protect public health via prudent regulation and timely policymaking. Better information is needed for proven measures of trial and established use and on the long-term trajectories of those who try VNPs in terms of whether they would have otherwise initiated or continued to smoke. As better information becomes available, the model presented here can be updated and should be able to provide more accurate estimates of the public health impact of VNP use.

### Supplementary Data

Supplementary Tables 1–5 and Supplementary Figures 1–3 can be found online at <http://www.ntr.oxfordjournals.org>

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## Declaration of Interests

KMC has received grant funding from the Pfizer, Inc, to study the impact of a hospital-based tobacco cessation intervention, and has received funding as an expert witness in litigation filed against the tobacco industry. No other conflicts of interest are declared.

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