

# BMJ Open Impact of vaping introduction on cigarette smoking in six jurisdictions with varied regulatory approaches to vaping: an interrupted time series analysis

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## ABSTRACT

**Objective** We sought to quantify the impact of vaping introduction on cigarette smoking across settings with varied regulatory approaches to vaping.

**Design** Interrupted time series analysis, adjusted for cigarette tax levels.

**Setting** Four Canadian provinces, UK and Australia.

**Participants** Entire population of smokers in each country.

**Interventions** The year that vaping was widely introduced in each country.

**Primary and secondary outcome measures** The primary outcome is cigarette consumption per adult, and the secondary outcome is smoking prevalence among young adults.

**Results** Based on allowable nicotine levels, restrictions on e-cigarette advertising, sales and access, and taxation, the least to most restrictive jurisdictions were, in order, Alberta, Ontario, Quebec and British Columbia (all in Canada), UK and Australia. In most, but not all, settings where higher nicotine content was permitted in vaping products (66 mg/mL), vaping introduction led to a reduction in cigarette consumption per capita (Ontario:  $p=0.037$ , Quebec:  $p=0.007$ ) or in smoking prevalence among young adults (Alberta men,  $p=0.027$ ; Quebec men,  $p=0.008$ ; Quebec women,  $p=0.008$ ). In the UK, where the maximum permitted nicotine content in vaping products was 20 mg/mL, vaping introduction slowed the declining trend in cigarette smoking among men aged 16–24 years ( $p=0.031$ ) and 25–34 years ( $p=0.002$ ) but not in cigarette consumption per adult. In Australia, where nicotine was not permitted in e-cigarettes, e-cigarette introduction slowed the declining trend in cigarette consumption per capita and in smoking prevalence among men aged 18–24 years (cigarette consumption:  $p=0.015$ , prevalence:  $p=0.044$ ).

**Conclusion** In environments that enable substitution of cigarettes with e-cigarettes, e-cigarette introduction reduces overall cigarette consumption. Thus, to reduce cigarette smoking, policies that encourage adults to substitute cigarette smoking with vaping should be considered.

## Strengths and limitations of this study

- This study uses an interrupted time series (ITS) design, which provides credible evidence on the longitudinal effects of interventions where randomisation is not possible.
- We are able to assess e-cigarette introduction in the context of permissible nicotine levels and regulations for their use, which is appropriate when considering substitution effects of vaping on cigarette demand.
- Since our definition of the intervention year is based on the first year when nationally representative surveys included questions on e-cigarette use, there may be a delay in capturing the effect of the intervention, and the ITS results are sensitive to the intervention year.

## INTRODUCTION

Use of electronic nicotine delivery systems (ENDS) (also called ‘vaping’), particularly electronic cigarettes (e-cigarettes), has increased rapidly in many high-income countries since about 2010, especially among youths and young adults.<sup>1 2</sup> As an e-cigarette contains fewer of the toxic and carcinogenic chemicals that are in a conventional cigarette, e-cigarette use is believed to be less harmful than smoking, but not completely harmless, and the long-term risks of vaping remain unknown.<sup>3</sup> The net effect of e-cigarette use will depend on its harms and if e-cigarettes reduce cigarette smoking (harms for cigarette use are well documented, including a typical loss of a decade of life among lifelong cigarette smokers).<sup>1 4</sup>

Numerous studies have found or supported the view that among youths and young adults, vaping acts as a substitute for cigarette smoking.<sup>5–8</sup> However, the degree of substitution also depends on government regulations



on vaping such as whether nicotine is permitted in vaping devices, maximum permissible nicotine content, minimum age for purchase and tax on e-cigarettes, as well as the regulatory and taxation environment for cigarettes. To date, to the best of our knowledge, no studies have examined the impact of vaping introduction on cigarette smoking across settings with varied regulatory approaches to vaping.

This study aims to quantify the impact of vaping introduction on cigarette smoking in six high-income jurisdictions that vary in regulatory approaches to vaping: four provinces of Canada and UK and Australia, using interrupted time series (ITS) analysis. We hypothesise that in settings where regulations favour the uptake of vaping (such as higher permissible nicotine level in vaping devices, greater access to e-cigarettes, and low or no tax on e-cigarettes), vaping introduction has led to a faster decline in cigarette smoking based on aggregate sales of legal (non-contraband) cigarettes. Our secondary outcome is smoking prevalence among youths and young adults, stratified by sex.

## METHODS

### Choice of jurisdictions

We selected Canada, UK and Australia as jurisdictions that have adopted varied regulatory approaches to vaping based on differential levels of vaping regulations<sup>9 10</sup> and availability of data on e-cigarette use and smoking. In Canada, vaping regulations vary substantially across provinces, hence necessitating a province-specific examination. We selected Alberta, British Columbia (BC), Ontario and Quebec provinces in Canada, as they account for about 85% of Canada's young adult population (aged between 18 and 34 years) and total cigarette sales.<sup>11 12</sup> For each of the six selected jurisdictions, we examined the regulations on vaping products as they pertain to the maximum permissible nicotine content in the products, minimum age for purchase and sales, marketing, and advertisement of the products. Based on these criteria, we then classified the jurisdictions along the range from 'less restrictive' to 'most restrictive'. Across these settings, regulation of cigarette smoking is fairly similar, with generally high excise taxes on cigarettes (for which we adjust in our analysis); restrictions on tobacco advertising, sales and promotion; and use of prominent health warning labels on cigarette packaging.<sup>13</sup>

### Measure of e-cigarette use and cigarette smoking

We examined the trends in prevalence of current e-cigarette use or e-cigarette use in the past 30 days, reported by national surveys in Canada, UK and Australia from 2012 (or the year when surveys first collected data on e-cigarette use) to 2019. The survey sources are presented in the Data sources section.

Our primary outcome was annual cigarette consumption per adult, which we defined as individuals aged 18 years and over. Annual cigarette consumption is measured

as the number of legal (non-contraband) cigarette sticks sold; in the UK and Australia, where these data were not available, we used the monetary value of cigarettes consumed per adult (at inflation-adjusted price). Out of the total annual cigarette consumption, consumption by youths and young adults, which we defined as individuals aged between 15 years and 30 years, accounted for about 30% across Canadian provinces (authors' calculation, insufficient data to estimate for the UK and Australia). For cigarette smoking among youths and young adults, we used prevalence of cigarette smoking between the age of 15 years and 30 years (age range varies by country, depending on data availability; see the Smoking prevalence section), stratified by sex. For countries where prevalence of cigarette smoking was not available, we used prevalence of any tobacco smoking, assuming that the majority of tobacco smoking comprises cigarette smoking.<sup>14</sup>

## Data sources

### Prevalence of current e-cigarette use

In Canada, we obtained prevalence of past 30 days' e-cigarette use, by province, from the Canadian Tobacco, Alcohol and Drugs Survey, which is the first national survey in Canada that included questions on e-cigarette use in 2013.<sup>15</sup> In the UK, we used prevalence of current e-cigarette use reported by Action on Smoking and Health based on annual surveys carried out online on over 12 000 adults aged 18 years and over in Great Britain.<sup>16</sup> The survey included questions on e-cigarette use for smokers from 2010 and for all adults from 2012.<sup>16</sup> For Australia, we used data from the National Drug Strategy Household Survey (NDSHS), which collects information on alcohol and tobacco consumption and illicit drug use every 2–3 years among Australians aged 14 years and older.<sup>17</sup> The NDSHS began reporting prevalence of e-cigarette use among the general population from 2016.

### Cigarette consumption

We estimated the annual cigarette consumption per adult in the Canadian provinces as the number of cigarette sticks consumed per adult, using cigarette sales data from Health Canada<sup>12</sup> and population data from Statistics Canada.<sup>11</sup> For the UK, we used cigarette retail sales value per adult using sales data, expressed as retail value in US dollars of 2018, from Euromonitor. For Australia, we used chain volume (which measures changes in quantity by holding price constant) of cigarettes and other tobacco products per adult expressed in Australian dollars of 2018, estimated by the Australian Bureau of Statistics.<sup>18</sup> The total cigarette consumption in the UK and Australia was then divided by the number of adults aged 18 years and older, estimated in the United Nations World Population Prospects 2019,<sup>19</sup> to obtain cigarette consumption per adult.

### Smoking prevalence

For Canada, we obtained prevalence of current cigarette smoking (daily or occasional) by province from the Canadian Community Health Survey.<sup>20</sup> In our study, we used the prevalence of cigarette smoking among individuals aged 18–34 from 2008 to 2018. Smoking prevalence estimates among younger age groups are unreliable due to small sample sizes<sup>20</sup>; hence, they were not used. For UK, we obtained cigarette smoking prevalence from the Opinions and Lifestyle Survey.<sup>21</sup> Although the Annual Population Survey collects smoking data in the UK, data prior to 2010 are not available. We used cigarette smoking prevalence among those aged 16–24 years and 25–34 years from 2007 to 2019. For Australia, we used prevalence of tobacco smoking among individuals aged 18–24 years and 25–34 years from 2001 to 2017 from the Australian National Health Survey (AHS).<sup>22</sup> The AHS is conducted every 2–3 years and reports prevalence of any tobacco smoking but not cigarette smoking.<sup>22</sup> As cigarette sales comprise about 85% of the overall sales of tobacco products in Australia,<sup>23</sup> we used tobacco smoking prevalence as a proxy for cigarette smoking prevalence.

### Tobacco tax/cigarette price

Our ITS model adjusted for tobacco tax or cigarette price as a potential confounder. For Canada, we obtained the annual federal and provincial tobacco tax rates from 2008 to 2018 from the Canadian Cancer Society<sup>24</sup> and Non-Smokers' Rights Association/Smoking and Health Action Foundation (2018).<sup>24 25</sup> For UK, we used data on the price of a 20-cigarette pack of the most sold brand obtained from the WHO Tobacco taxes and prices database.<sup>26</sup> For Australia, we used cigarette tax rates, as Australian dollar per kilogram of cigarettes, obtained from the Australian Bureau of Statistics.<sup>27</sup> All taxes and prices were adjusted for inflation by converting them to local currency units of 2018.<sup>28 29</sup>

### Statistical analysis

#### ITS analysis

We used ITS analysis to examine changes in the secular trend (slope change) in (1) cigarette consumption per adult and (2) smoking prevalence among youths and young adults, stratified by sex, after e-cigarette introduction in the selected settings with differential levels of vaping regulations. Details of the ITS methodology used and choice of intervention year can be found in the online supplemental material.

As a potential confounder for changes in cigarette consumption and smoking prevalence, we adjusted our model for major tobacco control measures implemented during the period examined in our study: plain packaging for cigarettes which was implemented in the UK in 2017 and in Australia in 2012 (entered as a categorical variable with '0' for the years prior to the implementation and '1' for years after the implementation),<sup>30</sup> and tobacco tax increase using inflation-adjusted tobacco tax or cigarette price, thereby allowing for expected non-linearity in the

ITS regression curve.<sup>31</sup> We did not control for smoke-free public places and bans on tobacco advertising, promotion and sponsorship, as they were already enforced before the period of our analysis. Any change in the slope (the rate of change) in cigarette sales or smoking prevalence with  $p < 0.05$  was considered statistically significant. All analyses were carried out in Stata V.15.1.<sup>32</sup>

### Sensitivity analysis

We conducted a sensitivity analysis by (1) using the relative rate of change in cigarette consumption and in smoking prevalence per year as the outcomes and (2) changing the intervention year such that the intervention year is the year prior to the intervention year used in the main analysis. Data were insufficient for carrying out sensitivity analysis by moving the intervention year 1 year ahead of the year used in the main analysis.

### Patient and public involvement

Patients or the public were not involved in this study.

## RESULTS

Table 1 shows the vaping regulations, in terms of maximum permissible nicotine content, minimum age for purchase and sales, marketing, and advertisement of e-cigarettes, in the six selected jurisdictions. Based on these regulations, the least restrictive to the most restrictive vaping environments are in order: Alberta, Ontario, Quebec, BC, UK and Australia. In Canada, the maximum nicotine level allowed in vaping devices during our study period was 66 mg/mL, which is more than three times the maximum allowed in the UK of 20 mg/mL.<sup>1 10</sup> In Australia, nicotine-containing e-cigarettes were not permitted unless prescribed for therapeutic purposes by a registered medical practitioner.<sup>33</sup> In Canada, UK, and Australia, where e-cigarettes were permitted, sales to persons under 18 years were prohibited, and marketing, advertisement and promotion of e-cigarettes were restricted.<sup>10</sup>

E-cigarettes are taxed only in the UK, where as consumer products they are subject to 20% value added tax (VAT), and if they are regulated as medicinal products, the VAT levied is 5%.<sup>10</sup> In contrast to more homogenous regulation across subregions in the UK and Australia, Canadian vaping regulations vary across provinces.<sup>34</sup>

### Prevalence of current e-cigarette use

Figure 1 shows the trend in prevalence of current e-cigarette use in the six selected jurisdictions for the years for which data were available. Across all study settings, the prevalence of current e-cigarette use was variable over time, but low overall (<7%).

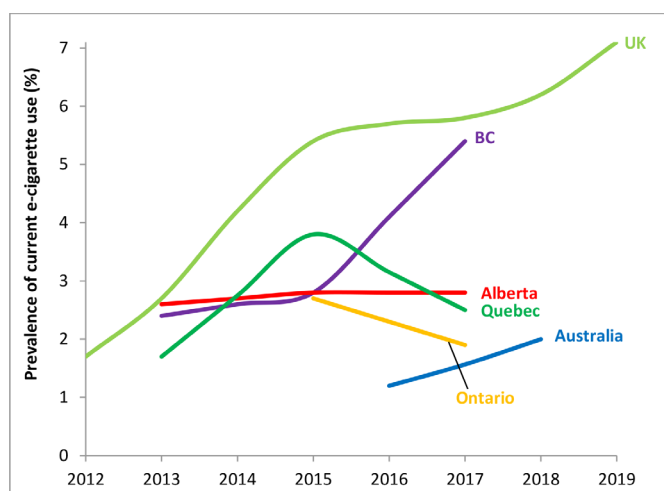
### ITS analysis

The coefficients for the underlying linear time trend and slope change after vaping introduction, and the tax (or price) and plain packaging variables from the ITS analysis of the impact of vaping introduction on cigarette consumption and smoking prevalence in the six selected

**Table 1** Vaping regulations by country and Canadian provinces during the study period<sup>10 16 30 34</sup>

Country/province	Maximum permissible nicotine content	Minimum age for purchase (years)	Sales, marketing and advertisement	Extent of vaping regulations
Alberta, Canada	66 mg/mL	18	Restricted locations for advertising and promotion	+ (less restrictive)
Ontario, Canada	66 mg/mL	19	Sales are banned where tobacco is banned.	+ (less restrictive)
Quebec, Canada	66 mg/mL	18	<ul style="list-style-type: none"> <li>▶ Sales are banned where tobacco is banned.</li> <li>▶ Use is banned where smoking is banned.</li> <li>▶ Advertising restrictions same as for tobacco.</li> <li>▶ Shops only allowed to show availability and price.</li> </ul>	++ (somewhat restrictive)
British Columbia, Canada	66 mg/mL	19	<ul style="list-style-type: none"> <li>▶ Sales are banned where tobacco is banned.</li> <li>▶ Use is banned where smoking is banned.</li> <li>▶ Advertising restrictions same as for tobacco.</li> <li>▶ Promotion is banned in stores, except point of sale showing price and availability.</li> </ul>	++ (somewhat restrictive)
UK	20 mg/mL	18	Restricted locations for advertising and promotion	+++ (more restrictive)
Australia	0 mg/mL	18	Advertising, promotion and sponsorship are prohibited.	++++ (most restrictive)

jurisdictions are shown in tables 2 and 3, respectively. In the ITS analysis, a slope change represents a change in the trend in smoking after vaping introduction relative to the trend before the introduction which we expect



**Figure 1** Prevalence of current e-cigarette use in the UK (aged 18+), Canada (aged 15+, by province) and Australia (aged 18+).

would have been unchanged had there been no e-cigarettes.<sup>35</sup> The trends in cigarette consumption per adult and smoking prevalence among youths and young adults are presented in online supplemental figure S1. All analyses are adjusted for changes in cigarette price or tax. In most settings, we found a secular decline in cigarette consumption per adult before vaping introduction except in Quebec where it increased modestly between 2008 and 2015 (table 2).

#### Cigarette consumption

##### *Less restrictive vaping environment (+)*

In Alberta, between 2008 and 2011, cigarette consumption per adult declined significantly annually by 27 sticks (95% CI -50 to -4). After the introduction of e-cigarettes in 2012, the rate of decline in cigarette consumption slowed by 34 sticks per year (95% CI -13 to 80) and was not significant. In Ontario, after e-cigarette introduction in 2015, cigarette consumption per adult declined significantly faster during 2015–2018 relative to during 2011–2014 by 90 sticks per year (95% CI -171 to -10).

**Table 2** Impact of vaping introduction on cigarette consumption from interrupted time series analysis, after adjusting for cigarette tax/price and plain packaging

Settings	Vaping restrictions (least to most)	Intervention year	Coefficients after adjusting for cigarette tax/price and plain packaging			Years of observations
			Underlying linear time trend	Trend change after vaping introduction	Tax/price*	
Alberta, Canada	+	2012	<b>-27.12 (-49.90 to -4.33, 0.032)</b>	33.52 (-13.36 to 80.40)	<b>-13.16 (-24.79 to -1.52, 0.037)</b>	8
Ontario, Canada	+	2012	45.00 (-25.70 to 115.71)	<b>-90.39 (-170.82 to -9.95, 0.037)</b>	2.54 (-54.36 to 59.43)	8
Quebec, Canada	++	2012	<b>86.34 (34.87 to 137.81, 0.013)</b>	<b>-116.72 (-172.05 to -61.37, 0.007)</b>	-6.47 (-13.01 to 0.07)	8
BC, Canada	++	2012	<b>-34.74 (-59.88 to -9.60, 0.022)</b>	-6.84 (-41.9 to 28.26)	1.27 (-9.37 to 11.91)	8
UK	+++	2011	-9.18 (-20.17 to 1.80)	6.95 (-1.68 to 15.58)	1.47 (-34.53 to 37.47)	8
Australia	++++	2015	<b>-75.02 (-148.01 to -2.04, 0.048)</b>	<b>119.91 (55.64 to 184.18, 0.015)</b>	-0.75 (-1.84 to 0.34)	8

Cigarette consumption is measured as number of cigarette sticks sold per adult in Canada, cigarette retail value per adult (2018 US\$) in the UK, and cigarette chain volume per adult (2018 \$A) in Australia.

The constant terms are 2516.83 for Alberta, 767.52 for Ontario, 1290.18 for Quebec, 918.38 for BC, 500.59 for UK and 1843.70 for Australia.

Values in bold are statistically significant at 95% CI.

\*For cigarette tax/price, we used cigarette tax per 200 sticks (in \$C) in Canada, price of a 20-cigarette pack of the most sold brand (in British £) for the UK and tax per kilogram of cigarettes (in \$A) in Australia. All taxes and prices are inflated to currency units of 2018. BC, British Columbia.

#### *Environment with somewhat restrictive regulations on vaping (++)*

In Quebec, cigarette consumption per adult was increasing significantly during 2011–2014 by 86 sticks per year (95% CI 35 to 138) but declined significantly faster annually after e-cigarette introduction compared with before (-117 sticks per year, 95% CI -172 to -61). In BC, after e-cigarette introduction, cigarette consumption per adult declined faster but was not statistically significant (-7 sticks, 95% CI -2 to 16).

#### *More restrictive vaping environment (++++)*

In the UK, between 2007 and 2010, cigarette consumption, in terms of retail sales value per adult, declined by US\$9 annually (95% CI -20 to 2) but was not significant. With e-cigarette introduction in 2011, the declining trend in cigarette consumption slowed by US\$7 per adult annually (95% CI -2 to 16), although this difference in the rate of decline was not statistically significant.

#### *Most restrictive vaping environment (++++)*

In Australia, between 2011 and 2014, cigarette consumption, in terms of chain volume per adult, was declining significantly by \$A75 per year (95% CI -\$A148 to -\$A2). After e-cigarette introduction in 2015, the declining trend significantly slowed during 2015–2018 compared with during 2011–2014 (\$A120, 95% CI \$A56 to \$A184).

In the sensitivity analysis when we examined the impact of vaping introduction on the relative rate of decline in cigarette consumption over time, similar results were found across jurisdictions (online supplemental table S1). In Alberta, BC and the UK, there was insufficient evidence to detect a difference in cigarette consumption patterns

before and after e-cigarette introduction. In Ontario and Quebec, the relative rate of decline in cigarette consumption per adult increased significantly after e-cigarette introduction, whereas in Australia, it decreased significantly after e-cigarette introduction. However, in the sensitivity analysis when the intervention is moved back 1 year from the year used in the main analysis, we found insufficient evidence to detect any difference in cigarette consumption per adult across the six jurisdictions (online supplemental table S2).

#### *Smoking prevalence among young adults*

##### *Less restrictive vaping environment (+)*

In Alberta, after e-cigarette introduction in 2012, the secular declining trend in smoking prevalence among men aged 18–34 years accelerated significantly by 3.21% per year (95% CI -5.74 to -0.69, table 3). For young adult women in Alberta and young adult men and women in Ontario, we found insufficient evidence to detect any difference in smoking prevalence before and after e-cigarette introduction. Sensitivity analyses conducted by moving back the intervention year 1 year from the year used in the main analysis showed similar results (online supplemental table S2).

##### *Somewhat restrictive vaping environment (++)*

In Quebec, after e-cigarette introduction in 2012, smoking prevalence among young adults declined significantly faster during 2012–2015 relative to during 2008–2011 for both men and women. In BC, the declining trend in smoking prevalence slowed by 0.05% for men (95% CI -3.38% to 3.48%) but accelerated by 0.12% for women

**Table 3** Impact of vaping introduction on smoking prevalence from interrupted time series analysis, after adjusting for cigarette tax/price and plain packaging

Settings	Vaping restrictions (least to most)	Intervention year	Coefficients after adjusting for cigarette tax/price and plain packaging				Years of observations
			Underlying linear time trend	Trend change after vaping introduction	Tax/price	Constant	
<b>Alberta, Canada (aged 18–34 years, * %)</b>							
Men	+	2012	0.55 (–1.21 to 2.32)	<b>–3.21 (–5.74 to –0.69, 0.027)</b>	–0.44 (–0.96 to 0.08)	<b>64.59 (27.60 to 101.58)</b>	8
Women	+		<b>–1.30 (–2.42 to –0.17, 0.035)</b>	–0.22 (–4.61 to 4.17)	0.16 (–0.94 to 1.26)	16.39 (–65.38 to 98.17)	8
<b>Ontario, Canada (aged 18–34 years*, %)</b>							
Men	+	2012	–0.60 (–4.17 to 2.97)	–0.81 (–3.95 to 2.34)	0.51 (–0.55 to 1.57)	–0.95 (–66.16 to 64.27)	8
Women	+		–0.30 (–2.39 to 1.79)	–1.43 (–3.67 to 0.80)	–0.09 (–0.88 to 0.70)	27.53 (–22.73 to 77.79)	8
<b>Quebec, Canada (aged 18–34 years, * %)</b>							
Men	++	2012	–0.62 (–2.17 to 0.93)	<b>–4.47 (–6.72 to –2.21, 0.024)</b>	<b>0.50 (0.23 to 0.77, 0.010)</b>	9.24 (–5.25 to 23.73)	8
Women	++		0.25 (–2.55 to 3.05)	<b>–5.62 (–8.47 to –2.77, 0.008)</b>	<b>0.86 (0.58 to 1.15, 0.002)</b>	<b>–19.43 (–32.92 to –5.94, 0.019)</b>	8
<b>British Columbia, Canada (aged 18–34 years, * %)</b>							
Men	++	2012	<b>–5.80 (–7.70 to –3.89, 0.002)</b>	0.05 (–3.38 to 3.48)	<b>1.15 (0.24 to 2.06, 0.027)</b>	–32.94 (–83.48 to 17.60)	8
Women	++		–0.79 (–3.26 to 1.68)	–0.12 (–2.62 to 2.37)	–0.05 (–0.61 to 0.50)	23.21 (–9.13 to 55.56)	8
<b>UK (aged 16–24 years, %)</b>							
Men	+++	2011	–2.81 (–7.22 to 1.59)	<b>1.88 (0.33 to 3.42, 0.031)</b>	7.17 (–14.70 to 29.04)	–22.63 (–171.44 to 126.19)	8
Women	+++		–1.16 (–5.89 to 3.56)	–0.63 (–3.40 to 2.13)	2.00 (–13.39 to 17.39)	13.57 (–91.44 to 118.59)	8
<b>UK (aged 25–34 years, %)</b>							
Men	+++	2011	<b>4.28 (3.23 to 5.34, 0.001)</b>	<b>2.07 (1.46 to 2.68, 0.002)</b>	<b>–25.47 (–30.12 to –20.83, 0.000)</b>	<b>202.79 (171.28 to 234.30)</b>	8
Women	+++		1.29 (–1.48 to 4.06)	–0.39 (–1.67 to 0.89)	–3.90 (–17.96 to 10.16)	50.17 (–45.78 to 146.12)	8
<b>Australia (aged 18–24 years, based on AHS, %)</b>							
Men	++++	2015	–0.68 (–2.97 to 1.60)	<b>3.77 (0.23 to 7.32, 0.044)</b>	–0.01 (–0.07 to 0.03)	<b>29.95 (6.22 to 53.68)</b>	8
Women	++++		–0.68 (–2.84 to 1.48)	–2.00 (–5.29 to 1.28)	0.01 (–0.04 to 0.05)	14.23 (–7.78 to 36.24)	8
<b>Australia (aged 25–34 years, based on AHS, %)</b>							
Men	++++	2015	–1.09 (–2.18 to 0.00)	–1.09 (–2.80 to 0.61)	0.01 (–0.01 to 0.03)	23.36 (11.95 to 34.78)	8
Women	++++		–0.71 (–4.78 to 3.36)	1.57 (–4.65 to 7.79)	–0.02 (–0.11 to 0.07)	30.06 (–11.63 to 71.74)	8

\*Among young adults aged 18–34 years from 2008 to 2014 and 20–34 years from 2015 to 2018.

†Cigarette smoking prevalence in Canada and UK, and tobacco smoking prevalence in Australia. AHS, Australian National Health Survey.

(95% CI -2.62% to 2.37%), although the changes in the trend for both are insignificant.

#### *More restrictive vaping environment (++++)*

In the UK, after e-cigarette introduction in 2011, the declining trend in smoking prevalence among men aged 16–24 during 2007–2010 slowed significantly by 1.88% per year (95% CI 0.33% to 3.42%) during 2011–2014. Among men aged 25–34 years, smoking prevalence was increasing by 4.28% (95% CI 3.23% to 5.34%) annually between 2007 and 2010. With e-cigarette introduction in 2011, the increasing trend in smoking prevalence increased significantly by 2.07% (95% CI 1.46% to 2.68%) during 2011–2014.

#### *Most restrictive vaping environment (++++)*

In Australia, after e-cigarette introduction in 2015, compared with those during 2011–2014, smoking prevalence among men aged 18–24 years declined significantly slower annually for men. Sensitivity analysis using the relative rate of change over time as the outcome showed similar results. However, when the intervention year is changed to 2014, we found insufficient evidence to detect a difference in the rate of change in prevalence before and after e-cigarette introduction.

In the sensitivity analysis using the relative rate of change in cigarette consumption and smoking prevalence over time as the outcomes, we found similar results across all six jurisdictions. However, when the intervention year is changed to 1 year prior to the intervention year used in the main analysis, we found insufficient evidence of the impact of e-cigarette introduction on the change in the trend of smoking prevalence among young adults.

## DISCUSSION

This study used ITS to analyse the impact of vaping introduction on cigarette smoking in six jurisdictions with varied approaches to vaping regulations. Across the Canadian provinces of Alberta, Ontario, Quebec and BC, where vaping regulations are less or somewhat restrictive, we found evidence that cigarette smoking (in terms of consumption or prevalence among young adults or both) declined significantly faster following e-cigarette introduction. In the UK, where vaping regulations are more restrictive, and in Australia, where vaping regulations were (and still are) highly restrictive, we found that vaping introduction has slowed the secular declining trends in cigarette smoking. Our findings suggest that, while e-cigarettes may be substitutes for cigarettes, actual substitution depends on the regulatory environment around vaping, such as nicotine content and tax on vaping products in the setting, and supports our hypothesis that in settings where regulations favour the uptake of vaping, vaping introduction had led to a faster decline in cigarette smoking.

Unlike Canada and the UK, where nicotine is permitted in e-cigarettes (although the maximum permissible

content varies by country), in Australia, sale of e-cigarettes containing nicotine is banned under the argument that nicotine in vaping products would lead young people who would otherwise not take up cigarette smoking to smoke.<sup>33 36</sup> Our finding that e-cigarette introduction has slowed the declining trends of smoking in Australia, which could be attributed to the nicotine ban in e-cigarettes, falls in line with several studies among adolescents in the USA that found that banning e-cigarette sales is significantly associated with an increase in smoking,<sup>37–39</sup> and supports Lillard's (2020) model on the economics of nicotine consumption in which nicotine is the primary object that e-cigarette consumers demand.<sup>40</sup> This limits the number of data points post intervention in our analysis, particularly with data from the AHS survey, which is only conducted every 2–3 years. Hence, continued monitoring of both cigarette and e-cigarette use among youths and young adults is needed in order to examine the impact of e-cigarette uptake on smoking more precisely.

Based on our findings from the perspective of tobacco harm reduction, at least in Canada and the UK where e-cigarette use has accelerated the rate of smoking decline among youths and young adults, controlled access to vaping could contribute to further curbing smoking rates in the long run. The net reduction in overall smoking was small—less than 2% vs baseline trends in Canada (data not shown)—consistent with the low level of e-cigarette use. Across Canada and the UK, the total volume of cigarettes consumed in 2017 was 63 billion sticks. Given that every 1.0–1.2 million sticks will eventually cause one death,<sup>1</sup> this means that about 63 000 deaths can be expected eventually, unless there are notable increases in cessation from current levels. Any meaningful reduction in cigarette consumption will reduce the leading cause of adult death in these countries, and the net benefit or harm of vaping must consider offsetting decreases in cigarettes. Imposing differential taxes on ENDS to encourage switching from the most harmful tobacco products (ie, cigarettes) to the least harmful ones could be another strategy.<sup>41 42</sup> Our study also found different impacts of vaping introduction on smoking among men and women. Further studies are needed to examine whether there are differential impacts by socioeconomic status, race and other characteristics.

Our study has several limitations. First, our definition of the intervention period for Canada, UK and Australia, which plays a major role in the ITS model, is based on the first year when national surveys included questions on e-cigarette use in the general population. Hence, there may be a delay in capturing the effect of the intervention, particularly as countries were experiencing significant declines in smoking prevalence in the years preceding the assigned intervention date in the ITS. However, sensitivity analysis using relative rate of decline over time as the outcome found similar results. In addition, based on the first national survey that collected data on e-cigarette use, the prevalence was under 3% across all settings included in this study. Second, in this study, the ITS model assumes that without the introduction of e-cigarettes, the trend



in smoking (cigarette consumption and smoking prevalence) would remain unchanged during the postintervention period. However, across the jurisdictions selected for this study, there has been a long-term secular decline in smoking. Hence, the decline in smoking observed preintervention is likely to continue post intervention. Third, our main outcome was legal cigarette consumption measured using legal sales and did not include contraband sales, which account for about 15%–20% of total cigarette sales.<sup>43–45</sup> Fourth, our secondary outcomes, age-specific and sex-specific smoking prevalence among youths and young adults, were obtained from self-reported surveys. Hence, there could be an under-reporting of smoking due to social desirability bias, which might be greater in younger adults. Similarly, the prevalence of e-cigarette use could also be under-reported. Fifth, while examining the impact of vaping introduction on smoking prevalence, we did not account for the impact on smoking intensity and frequency. Additionally, we did not perform a test to examine the relationship between restrictions defined by maximum permissible nicotine content in vaping products to other variables such as minimum age for purchase, and restrictions around marketing of vaping products and the trend in smoking. As of 23 July 2021, Canada lowered the maximum permissible nicotine content in vaping products to 20 mg/mL.<sup>46</sup> Future studies would need to examine the impact of this restriction and restrictions on sales, advertisement and marketing of vaping products on the trend in smoking prevalence to directly establish a link between vaping restrictions and cigarette smoking. Finally, we did not control for vaping regulations which may indirectly impact smoking behaviour.

Despite these limitations, our study showed the impact of vaping introduction on cigarette consumption and smoking prevalence among youths and young adults in four high-income countries that have adopted different approaches to vaping regulation, using ITS while controlling for the secular trends in smoking decline and major tobacco control measures adopted by jurisdictions during the period examined.

## CONCLUSION

This study used ITS analysis to examine the impact of vaping introduction on smoking in six high-income jurisdictions that have adopted varied regulatory approaches to vaping. Our findings showed that in most, but not all, settings where policies enable substitution of cigarettes with e-cigarettes, vaping introduction has accelerated the rate of decline in smoking, whereas in settings that restrict the uptake of e-cigarettes or do not permit the use of nicotine in e-cigarettes, vaping introduction has slowed the secular rate of decline in smoking.

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**Data availability statement** Data used in this study are available in public, open access repositories. Data are available upon reasonable request to the corresponding author. The dataset used in the study is publicly available from the countries' government website (see the Data sources subsection in the Methods section) or by request to the last author (PJ).

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