

# Is it safe to vape? Assessing the carcinogenic risk of “vape smoke”

Ian C Shaw, Ashleigh R Woollett, Natasha M Dickie, Madison J Kennedy, Jacob T Liddle, Leila BM Nolan, Megan Rawlins

## ABSTRACT

Vaping was introduced as a means of quitting smoking by slowly reducing nicotine dose to wean smokers of their carcinogenic habit. In this setting the risks of vaping likely outweigh the benefits of eliminating the carcinogenic risk associated with smoking cigarettes. Soon after the introduction of vaping it caught on as a trendy alternative to smoking, particularly among young people. This means that the risk–benefit profile changed considerably because the benefit of smoking cessation was no longer part of the risk–benefit equation. Since vaping has now become a primary means of taking nicotine, a risk assessment of vaping per se is necessary to determine its potential effects on vapers’ health. In this viewpoint, we use our knowledge of the chemistry of the production of “vape smoke” to identify its key toxic components. Then, using published animal toxicity data for these chemicals and estimates of vapers’ exposure levels, we assess the magnitude of carcinogenic risk. We conclude that vaping is carcinogenic, but that the risk is likely lower than for smoking cigarettes. Therefore, someone taking up vaping not as a tool for smoking cessation is adding carcinogenic risk to their daily risk profile.

The modern vape was developed by Chinese pharmacist Hon Lik after his father died of lung cancer and he wanted to quit smoking himself. The first-generation design, known as “cig-a-like”, resembled a conventional cigarette and was marketed as an aid to quit smoking. More recent designs have moved away from a traditional cigarette lookalike to trendy flavoured vape pens and pods.

Modern vape devices have four components: battery, heating coil, fluid compartment and mouthpiece. The vape liquid, which comprises solvents and vapour-producing chemicals, flavours and nicotine, is passed over the heating coil, vaporised and delivered to the consumer via the mouthpiece. Some reusable vapes have coils designed to allow users to customise vapour (we will use the term “vape smoke” to describe the inhaled vapour, but acknowledge that technically it is an aerosol) produced to suit their personal needs. The ultimate purpose of the device is to deliver a drug (usually nicotine) to the consumer via the vape smoke. The use of flavouring agents customises the experience to suit the consumer’s taste. This is controversial because it might increase the willingness of adolescents to take up vaping and lead to nicotine addiction. Indeed, the introduction of “youthful flavours” has led to a significant increase in nicotine consumption among youths, especially those who have never smoked conventional cigarettes.<sup>1</sup>

In New Zealand, vaping is more common than conventional cigarette smoking in all age groups up to 45 years old, with more than 22% of 15–24-year-olds vaping.<sup>1</sup> This is concerning because there have been no long-term studies on regular vape consumers, meaning that the long-term health risks remain uncertain.

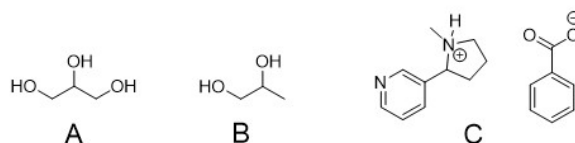
Since it will be many years before an epidemiological study on the carcinogenic risk of vaping can be carried out, in this viewpoint we combine what is known about the chemistry of vape liquid components under vaping conditions with published animal and *in vitro* studies to predict the carcinogenic risk of vaping.

## Vape liquid

Vape liquid (also called “vape juice” or “e-liquid”) has four key components: propylene glycol (propane-1,2-diol), glycerine (propane-1,2,3-triol), nicotine (usually as the benzoate salt, which vaporises at a lower temperature than free-base nicotine) and flavours (Figure 1).

Propylene glycol and glycerine act both as solvents for nicotine and the flavours and generate vape smoke’ when heated. The combination of glycerine and propylene glycol determines the smoothness or quality of the vape smoke, which makes the process pleasurable for its consumer. Nicotine is addictive and makes the consumer crave vaping. The flavouring agents are generally

**Figure 1:** Glycerine (propane-1,2,3-triol, A), propylene glycol (propane-1,2-diol, B) and nicotine benzoate (C).



not disclosed on the label: they include menthol, cinnamaldehyde, vanillin, benzaldehyde, ethyl maltol and dimethylpyrazine, all of which have toxicological profiles in their own right, but little is known about their pyrolysis products and since they are present at low concentrations in the vape liquid they are likely of less toxicological concern.<sup>2</sup>

Glycerine and propylene glycol are both authorised for use in food products in many jurisdictions worldwide and are generally regarded as safe (GRAS). However, this is a very misleading assurance in the context of their use in vape devices because they are inhaled (GRAS relates only to oral exposure) and the vape process involves heating, which leads to thermal degradation forming toxic aldehydes.<sup>3</sup> It is the toxicity of the inhaled aldehydes that likely determines the long-term health risks of vaping.

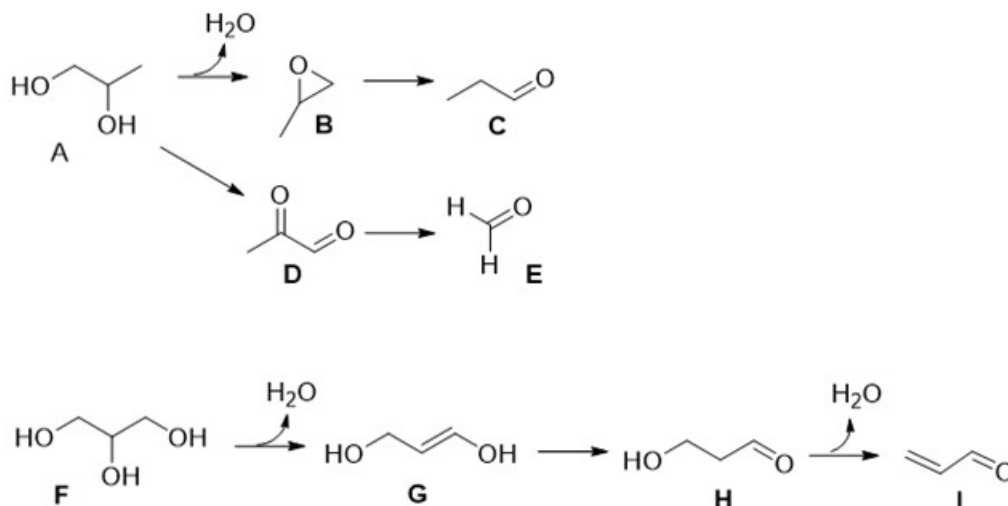
In this viewpoint we outline the chemistry of the vape process, particularly the toxicological consequences of thermal decomposition of vape liquid components, and assess the magnitude of the long-term health risks to regular vape consumers.

## Thermal decomposition of vape liquid components

The temperature of the heating coil is in the range 157–266 degrees Celsius with a “usual” vaping temperature of approximately 190 degrees Celsius.<sup>4</sup> At this temperature, propylene glycol (boiling point: 187 degrees Celsius) readily forms a vapour for inhalation, while glycerine (boiling point: 290 degrees Celsius) vaporises to a lesser extent. Users can, to some extent, personalise their vaping experience by varying the combination of propylene glycol and glycerine or adjusting the coil’s operating temperature to alter the “quality” of the vape smoke.

At normal operating temperature (approximately 190 degrees Celsius), both propylene glycol and glycerine break down to form aldehydes including acrolein, formaldehyde, acetaldehyde, propionaldehyde and methylglyoxal (Figure 2). The degree of thermal decomposition and the thermal decomposition pathways are temperature dependent and so vary from device to device and from user to user.

**Figure 2:** Top: thermal decomposition of propylene glycol (A) via propylene oxide (B) to propionaldehyde (C) and via methylglyoxal (D) to formaldehyde (E).<sup>3</sup> Bottom: thermal decomposition of glycerine (F) via 1,3-dihydroxypropane (G) and 3-hydroxypropanal (H) to acrolein (I).<sup>5</sup>



The aldehydes shown in Figure 2 are toxic following inhalation. Their mechanisms of toxicity range from direct reactions (e.g., alkylation) with biological molecules (e.g., DNA) due to the chemical reactivity of the aldehyde group to initiation of a local inflammatory response due to the chemicals' irritant properties. These mechanisms can lead to significant cellular and physiological outcomes, including carcinogenesis and inflammation-related disorders. In this viewpoint we focus on carcinogenesis.

The toxicology of aldehydes, particularly formaldehyde, has been studied extensively because of their applications in industrial processes. Formaldehyde is of note because of its use in pathology laboratories. Therefore, previous human exposure/effect data (high incidence of nasal cancers in exposed workers) led to its categorisation by the World Health Organization (WHO) International Agency for Research on Cancer (IARC) as Group 1—*carcinogenic to humans*. To understand the risk of vaping, we must assess the hazard (i.e., toxicity) of the aldehydes present in vape smoke and estimate vapers' exposure levels. These two parameters allow us to estimate the magnitude of risk ( $RISK=HAZARD \times EXPOSURE$ ).

## Formaldehyde

Formaldehyde is a human respiratory carcinogen. Formaldehyde's carcinogenic properties are thought to be due to its reactive aldehyde group causing DNA/protein crosslinks in exposed (e.g., nasal) tissues.<sup>6</sup> There is overwhelming evidence for multiple-site carcinogenesis in humans occupationally exposed to formaldehyde.<sup>6</sup> However, assessing the dose at which carcinogenesis occurs is difficult because of the very long-term and variable exposures in industrial and laboratory settings. For this reason we will use published animal toxicology studies to estimate the carcinogenicity adverse effect levels as part of our human risk assessment.

In a study in which rats were exposed to formaldehyde vapour for 24 months and the cancer incidence compared to controls, there was a definite dose relationship for nasal squamous cell carcinoma with a high incidence at 14.3 parts per million (ppm).<sup>7</sup> More recently, Gelbke et al. reassessed the wealth of published formaldehyde toxicity data and proposed an inhalation carcinogenicity lowest observed adverse effect concentration for polyploid adenomas of 1 ppm.<sup>8</sup>

Studies on vape inhalation have shown that

vape devices deliver very variable formaldehyde/puff values with a mean of 7.8mcg.<sup>9</sup> This variability is further evidenced by Margham et al., who reported formaldehyde/puff values between 17.5 and 59.0mcg.<sup>10</sup> In addition, Farsalinos et al. showed that formaldehyde concentrations in vape smoke are dependent on coil voltage (this determines coil temperature) and ranged from almost 0mcg/puff at 3.3V to approximately 71mcg/puff at 5.0V.<sup>11</sup> The WHO reported that the formaldehyde concentration in cigarette smoke is approximately 5mcg/puff.<sup>12</sup> At a realistic vape coil voltage of 4V, the formaldehyde delivered is approximately 32% lower than that through a conventional cigarette (note: the relationship between formaldehyde production and voltage is not linear).<sup>10</sup>

Klager et al. measured formaldehyde concentrations in vape smoke from four different vape liquid brands comprising 15 different flavours and reported concentrations in the range of 55.9mcg/m<sup>3</sup> (45.6ppm) to 99,400mcg/m<sup>3</sup> (81,011ppm).<sup>13</sup> These concentrations all exceed the rat 14.3ppm exposure concentration, which led to increased nasopharyngeal cancer incidence and exceeded the lowest observable adverse effect concentration of 1ppm.<sup>7</sup> The rat carcinogenicity studies involved constant prolonged inhalation exposure, whereas vaping results in relatively short inhalation exposures. We estimate that these short exposures occur approximately four times per day but are likely to be over many years. This means that it is impossible to determine quantitative cancer risk from vaping. However, there is no doubt that formaldehyde in vape smoke presents a cancer risk.

## Acrolein

Acrolein (prop-2-enal) is very reactive and highly toxic following both inhalation and oral exposure. It is a ubiquitous environmental pollutant (e.g., from combustion engine exhaust) and is present in many foods (e.g., daily consumption from fruit ~15–17mcg), so humans are exposed to low doses constantly.<sup>14,15</sup> In addition, acrolein is a major component of tobacco smoke: a cigarette produces 10 to >140mcg acrolein.<sup>15</sup>

Acrolein's mechanisms of toxicity are underpinned by its chemical reactivity, leading to adduct formation with DNA and proteins causing functional alterations of key biological molecules.<sup>14</sup> Acrolein is detoxified by reaction with cell protective glutathione and after further

metabolism is excreted.<sup>16</sup>

Regardless of exposure source, acrolein's effects on cells will be the same. Therefore, acrolein from vaping adds to the body's acrolein burden and depletes cellular glutathione, thus exposing cells to toxic insults that glutathione would normally protect against. If acrolein exposure is high enough to outstrip the cell's glutathione pool, glutathione-unreacted acrolein will be available to react with other biological molecules (e.g., DNA), thus exerting its toxic effects.

Acrolein has "low" mutagenicity in a bacterial reverse mutation assay.<sup>17</sup> In animal studies, acrolein is acutely toxic with inhalation LC<sub>50</sub>s ranging from 18 to 151mg/m<sup>3</sup> and oral LD<sub>50</sub>s in the range 7–46mg/kg body weight and continuous inhalation studies (90 days) lead to exposure-related lung, spleen and thyroid lesions with a lowest observable adverse effect level in dogs of 0.5mg/m<sup>3</sup>.<sup>18</sup> Long-term (52 weeks) inhalation studies at exposures of 9.2mg/m<sup>3</sup> showed no exposure-related tumours,<sup>18</sup> suggesting that acrolein's low mutagenicity may not be relevant in a carcinogenicity context. Contrary to this, the IARC rates acrolein as Group 2A—*probably carcinogenic to humans* due to evidence that acrolein is carcinogenic in a dose-related manner in animal studies, but its carcinogenicity in humans has not been proven or disproven.

In rats at an acrolein inhalation dose of 2ppm there was a significant increase in respiratory tract inflammation and squamous cell metaplasia with goblet cell hyperplasia, which is considered to be a preneoplastic change.<sup>19</sup> Multiple exposures to the same carcinogen with the same cancer outcome are likely to be additive and therefore we use the dose leading to respiratory hyperplasia as the trigger dose for carcinogenesis in this risk assessment.<sup>19,20</sup>

Acrolein concentration in vape smoke is in the range 0.012–1.37mcg/puff and 12.4–19.2mcg/puff.<sup>9,10</sup> The volume of a vape puff ranges from 90 to 150mL. At the highest concentration of acrolein, 19.2mcg/puff, the acrolein exposure is in the range 128–213mcg/L. Since the trigger hyperplasia exposure concentration in rats is 2ppm, which equates to approximately 5mcg/L,<sup>19</sup> this means that a vaper's exposure to acrolein is above the hyperplasia trigger concentration. However, this relates only to the concentration in respired vape smoke and does not take account of exposure frequency or duration (i.e., total acrolein dose). In the rat study we used to define the hyperplasia trigger exposure concentration,

this was 6 hours a day, 5 days a week for a total of 104 weeks. In a vaper, exposure would be approximately four sessions a day for what is likely to be years. In view of this, the acrolein exposure concentration via vaping is arguably within the hyperplasia trigger range, but it is not possible to quantify the risk.

## Acetaldehyde

Acetaldehyde (ethanal) is a reactive environmental pollutant and is used in industrial processes, which means that human exposure studies are available. Indeed, these studies in combination with animal carcinogenicity studies led the IARC to rate acetaldehyde as Group 2B—*possibly carcinogenic to humans*. In addition, acetaldehyde is an alcohol dehydrogenase catalysed metabolite of ethanol and has been linked to oesophageal cancer in alcoholics.<sup>22</sup>

Acetaldehyde is detoxified to non-toxic acetate by aldehyde dehydrogenase, thus the speed and completeness of this detoxification pathway determine the amount of acetaldehyde available to react with biological molecules and so exert its toxic effects. Interestingly, acetaldehyde can also be detoxified by reaction with cysteine to form thiazolidine-4-carboxylic acid, which can, in turn, react with nitrite (e.g., from cured meats) to form carcinogenic N-nitrosothiazolidine-4-carboxylic acid.<sup>23</sup> This illustrates the multiple pathways by which acetaldehyde might initiate carcinogenesis.

Long-term rat acetaldehyde inhalation studies led to squamous cell carcinomas at or above 1,500ppm (equivalent to approximately 2,700mcg/L).<sup>24</sup> Acetaldehyde concentration in vape smoke is in the range 0.02–22.5mcg/puff and 7.71–18.0mcg/puff.<sup>9,10</sup> Using the same method of calculation used for acrolein (above) means that the worst case acetaldehyde exposure concentration is 150–250mcg/L, which is far below the rat study 2,702mcg/L trigger value. In the rat studies, this trigger value led to carcinogenesis following extended continuous exposure, whereas vaping exposure would be for relatively short bursts for probably years. Nevertheless, it is unlikely that this would pose a cumulative carcinogenic dose considering aldehyde dehydrogenase-mediated acetaldehyde detoxification. In addition, aldehyde dehydrogenase has been demonstrated in the nasal mucosa of rodents, which means that acetaldehyde detoxification might occur locally following inhalation,<sup>25</sup> further reducing carcinogenic risk.

On balance, acetaldehyde likely presents a low, if any, carcinogenic risk following vaping.

## Propionaldehyde

Toxicologically, propionaldehyde (propanal) is similar to formaldehyde and acetaldehyde because of their common reactive aldehyde groups. However, the length and form of the aldehyde carbon chain in part determines its reactivity; indeed, chain length is inversely related to inhalation toxicity.<sup>26</sup> Therefore, despite there being a dearth of toxicological data on propionaldehyde, it would be expected to have a lower toxicity than acetaldehyde.

Propionaldehyde concentration in vape smoke is in the range 0.019–12.1mcg/puff and 2.3–6.01mcg/puff.<sup>9,10</sup> Using the same method of calculation used for acrolein (above) the worst case propionaldehyde exposure concentration is 0.08–0.13mcg/L. This is very much lower than the trigger value of 2,700mcg/L for acetaldehyde, which, based on propionaldehyde's expected lower toxicity profile compared with acetaldehyde, suggests that propionaldehyde likely presents very low or no cancer risk.

## Methylglyoxal

Methylglyoxal (2-oxopropanal) is an aldehyde with a keto-containing side chain. Its toxicological profile is akin to the other aldehyde toxicities discussed above. It depletes cellular glutathione and so exposes cells to the toxic effects of molecules that would usually be detoxified by glutathione,<sup>27</sup> which might facilitate the toxicities (including carcinogenicity) of other molecules. In

this context, it is interesting that methylglyoxal increases the incidence of N-methyl-N'-nitro-N-nitrosoguanidine initiated tumours in rats.<sup>28</sup> In addition, methylglyoxal is positive in a mutagenicity test and the positive test result is suppressed by supplementing with glutathione.<sup>29,30</sup> This supports the glutathione depletion hypothesis for methylglyoxal-associated carcinogenesis. A significant amount of other published data led the IARC to rate methylglyoxal as Group 3—*not classifiable as to its carcinogenicity to humans*.

The concentration of methylglyoxal in vape smoke is in the range 5.24–6.49mcg/puff,<sup>10</sup> but considering its IARC carcinogenicity classification, it is very unlikely that inhalation exposure will initiate carcinogenesis. However, its presence might facilitate or enhance the carcinogenicity of carcinogens present in vape smoke.

## Dose versus exposure concentration

Risk is determined by dose. However, in an inhalation setting concentrations are often considered in the context of exposure time. In order to lead to a particular health outcome (in this case carcinogenesis) the exposure time to a particular concentration (e.g., of an aldehyde) is the risk determinant. In this viewpoint we have used concentration as an indicator of exposure level associated with risk, and we have calculated doses from these concentrations (Table 1) as a better determinant of magnitude of risk.

## Non-genotoxic carcinogenesis

Inflammation is a key driver of non-genotoxic

**Table 1:** Approximate yields of aldehydes from cigarette smoke and calculated doses for a 70kg human assuming the entire cigarette is consumed compared with equivalent data for vaping.<sup>9,31,32</sup>

Aldehyde	Smoking		Vaping	
	mcg/cigarette	Dose mcg/kg body weight	mcg/puff	Dose mcg/kg body weight
Acrolein	220–468	3.1–6.7	0.012–1.37	0.0026–0.29
Formaldehyde	87–243	1.2–3.5	0.13–24.4	0.028–5.2
Acetaldehyde	1,110–2,040	15.9–29.1	0.02–22.5	0.0043–4.8
Propionaldehyde	87–176	1.2–2.5	0.19–12.1	0.0041–2.6

carcinogenesis because it stimulates cell division and, since DNA-related errors can lead to neoplasia, if the frequency of division goes up the risk of carcinogenesis also goes up.<sup>33</sup>

Aldehydes initiate inflammatory responses at low inhalation concentrations in an environmental pollution setting, and aldehydes in cigarette smoke have been shown to cause acute airway inflammation.<sup>34</sup> The doses of some aldehydes in cigarette smoke and vape smoke are shown in Table 1.

Acrolein and acetaldehyde doses are higher following cigarette smoking than vaping, whereas formaldehyde and propionaldehyde doses are comparable (Table 1).

While acetaldehyde poses a low cancer risk, it represents a very much lower risk to vapers than to cigarette smokers. Acrolein, on the other hand, is mutagenic and carcinogenic, but the dose following vaping is very much lower than following smoking and so the cancer risk is concomitantly lower. The dose of formaldehyde, a known human carcinogen, is comparable between cigarette smoking and vaping, which suggests that the formaldehyde dose from vaping poses a comparable cancer risk to cigarette smoking. Similarly, the propionaldehyde dose is similar for cigarette smoking and vaping but likely poses negligible cancer risk. All of these aldehydes are inflammatory and so might present a non-genotoxic carcinogenesis risk both by primary cellular transformation (due to transcriptional errors in cell division) or promotion of already transformed (due to exposure to other carcinogens) cells.

Finally, the complex array of compounds that vapers inhale, including aldehydes, might act in concert leading to additivity or even synergy. Because all aldehydes share the reactive aldehyde group, their likely mechanisms of toxicity (including carcinogenicity) are similar, but the

extent varies depending on the length of their carbon chains' influence on reactivity. Therefore, aldehyde toxicity is likely to be at least additive. However, synergy is feasible because if a highly reactive aldehyde (e.g., formaldehyde) leads to a mutation and carcinogenesis, the transformation might be promoted by the inflammatory properties of other aldehydes (e.g., propionaldehyde) via a non-genotoxic mechanism.

## Conclusions

In our view, it is clear from this risk analysis that vaping presents an unquantifiable cancer risk, but that based on exposure to vape smoke aldehydes the risk is lower than for cigarette smoking. It is important to note that there are also other potent carcinogens in cigarette smoke (e.g., benzo[a]pyrene) that present a significantly higher cancer risk.

In our view this risk assessment supports the use of vaping for smoking cessation because the overall cancer risk is lower than for smoking, but does not exonerate vaping in its own right because taking up the habit introduces a new vaping-associated cancer risk.

It will take many years to accrue sufficient epidemiological data to determine whether or not vaping is carcinogenic. In the meantime, in our view, the risk assessment approach taken here points firmly to cancer risk, based purely on the inhaled carcinogenic components of vape smoke. This supports invoking the precautionary principle and the need to consider the vaping risk-benefit balance. There is a definite benefit of vaping as part of a smoking cessation programme, which likely outweighs the carcinogenic risk, but we find it difficult to identify any benefit of vaping for its own sake, which means that its predicted cancer risk is difficult, if not impossible, to justify.<sup>35</sup>

**COMPETING INTERESTS**

There are no conflicts of interest.

**ACKNOWLEDGEMENTS**

We thank Myles Landon and Matthew Goodwin for their involvement in the early stages of the preparation of the manuscript.

**AUTHOR INFORMATION**

Ian C Shaw: School of Physical & Chemical Sciences, University of Canterbury, Christchurch, New Zealand.  
 Ashleigh R Woollett: School of Physical & Chemical Sciences, University of Canterbury, Christchurch, New Zealand.  
 Natasha M Dickie: School of Physical & Chemical Sciences, University of Canterbury, Christchurch, New Zealand.  
 Madison J Kennedy: School of Physical & Chemical Sciences, University of Canterbury, Christchurch, New Zealand.  
 Jacob T Liddle: School of Physical & Chemical Sciences, University of Canterbury, Christchurch, New Zealand.  
 Leila BM Nolan: School of Physical & Chemical Sciences, University of Canterbury, Christchurch, New Zealand.  
 Megan Rawlins: School of Physical & Chemical Sciences, University of Canterbury, Christchurch, New Zealand.  
*The last five authors are listed alphabetically denoting their equal contributions to the work.*

**CORRESPONDING AUTHOR**

Ian C Shaw: School of Physical & Chemical Sciences, University of Canterbury, Christchurch, New Zealand.  
 E: [ian.shaw@canterbury.ac.nz](mailto:ian.shaw@canterbury.ac.nz)

**URL**

<https://nzmj.org.nz/journal/vol-139-no-1633/is-it-safe-to-vape-assessing-the-carcinogenic-risk-of-vape-smoke>

**CITATION**

Shaw IC, Woollett AR, Dickie NM, et al. Is it safe to vape? Assessing the carcinogenic risk of “vape smoke”. *N Z Med J.* 2026 Apr 17;139(1633):104-111. doi: 10.26635/6965.7434.

**REFERENCES**

- Nip J, Hoek J, Waa A. Vaping prevalence and trends: key findings in the 2022-23 NZ Health Survey [Internet]. Wellington, New Zealand: Public Health Communication Centre Aotearoa; 2023 Dec 19 [cited 2026 Feb 13]. Available from: <https://www.phcc.org.nz/briefing/vaping-prevalence-and-trends-key-findings-202223-nz-health-survey>
- Sachdeva J, Karunanathan A, Shi J, et al. Flavoring Agents in E-cigarette Liquids: A Comprehensive Analysis of Multiple Health Risks. *Cureus.* 2023;15(11):e48995. doi: 10.7759/cureus.48995.
- Jaegers NR, Hu W, Weber TJ, Hu JZ. Low-temperature (<200 °C) degradation of electronic nicotine delivery system liquids generates toxic aldehydes. *Sci Rep.* 2021;11(1):7800. doi: 10.1038/s41598-021-87044-x.
- Li Y, Burns AE, Tran LN, et al. Impact of e-Liquid Composition, Coil Temperature, and Puff Topography on the Aerosol Chemistry of Electronic Cigarettes. *Chem Res Toxicol.* 2021;34(6):1640-1654. doi: 10.1021/acs.chemrestox.1c00070.
- Bekki K, Uchiyama S, Ohta K, et al. Carbonyl compounds generated from electronic cigarettes. *Int J Environ Res Public Health.* 2014;11(11):11192-11200. doi: 10.3390/ijerph11111192.
- International Agency for Research on Cancer (IARC). Formaldehyde, 2-Butoxyethanol and 1-tert-Butoxypropan-2-ol. In: IARC Monographs on the Evaluation of Carcinogenic Risks to Humans Volume 88. Lyon: IARC; 2006 [cited 2026 Feb 6]. Available from: <https://publications.iarc.who.int/Book-And-Report-Series/Iarc-Monographs-On-The-Identification-Of-Carcinogenic-Hazards-To-Humans/Formaldehyde-2-Butoxyethanol-And-1--Em-Tert-Em--Butoxypropan-2-ol-2006>
- Kerns WD, Pavkov KL, Donofrio DJ, et al. Carcinogenicity of formaldehyde in rats and mice after long-term inhalation exposure. *Cancer Res.* 1983;43(9):4382-4392.
- Gelbke HP, Gröters S, Morfeld P. Lowest adverse effects concentrations (LOAECs) for formaldehyde exposure. *Regul Toxicol Pharmacol.* 2014;70(1):340-348. doi: 10.1016/j.yrtph.2014.07.016.
- Samburova V, Bhattarai C, Strickland M, et al. Aldehydes in Exhaled Breath During E-Cigarette Vaping: Pilot Study Results. *Toxics.* 2018;6(3):46. doi: 10.3390/toxics6030046.
- Margham J, McAdam K, Cunningham A, et al. The Chemical Complexity of e-Cigarette Aerosols Compared with the Smoke from a Tobacco Burning Cigarette. *Front Chem.* 2021;9:743060. doi: 10.3389/fchem.2021.743060.
- Farsalinos KE, Voudris V, Spyrou A, Poulas K. E-cigarettes emit very high formaldehyde levels only in conditions that are aversive to users: A replication study under verified realistic use conditions. *Food Chem Toxicol.* 2017;109 (Pt 1):90-94. doi: 10.1016/j.fct.2017.08.044.
- World Health Organization. Air quality guidelines for Europe, 2nd edition [Internet]. Denmark: World Health Organization Regional Office for Europe; 2000 Sep 21 [cited 2026 Feb 6]. Available from: <https://www.who.int/publications/i/item/9789289013581>
- Klager S, Vallarino J, MacNaughton P, et al.

- Flavoring Chemicals and Aldehydes in E-Cigarette Emissions. *Environ Sci Technol*. 2017;51(18):10806-10813. doi: 10.1021/acs.est.7b02205.
14. Moghe A, Ghare S, Lamoreau B, et al. Molecular mechanisms of acrolein toxicity: relevance to human disease. *Toxicol Sci*. 2015;143(2):242-255. doi: 10.1093/toxsci/kfu233.
  15. Henning RJ, Johnson GT, Coyle JP, Harbison RD. Acrolein Can Cause Cardiovascular Disease: A Review. *Cardiovasc Toxicol*. 2017;17(3):227-236. doi: 10.1007/s12012-016-9396-5.
  16. Stevens JF, Maier CS. Acrolein: sources, metabolisms, and biomolecular interactions relevant to human health and disease. *Mol Nutr Food Res*. 2008;52(1):7-25. doi: 10.1002/mnfr.200700412.
  17. Hemminki K, Falck K, Vainio H. Comparison of alkylation rates and mutagenicity of directly acting industrial and laboratory chemicals: epoxides, glycidyl ethers, methylating and ethylating agents, halogenated hydrocarbons, hydrazine derivatives, aldehydes, thiuram and dithiocarbamate derivatives. *Arch Toxicol*. 1980;46(3-4):277-285. doi: 10.1007/BF00310445.
  18. Gomes R, Meek ME, Eggleton M. Concise International Chemical Assessment Document 43: Acrolein [Internet]. Geneva: World Health Organization; 2002 [cited 2026 Feb 6]. Available from: <https://iris.who.int/server/api/core/bitstreams/fd793162-06d5-45c7-acc8-a9c9fe53439d/content>
  19. Matsumoto M, Yamano S, Senoh H, et al. Carcinogenicity and chronic toxicity of acrolein in rats and mice by two-year inhalation study. *Regul Toxicol Pharmacol*. 2021;121:104863. doi: 10.1016/j.yrtph.2021.104863.
  20. Burkart W, Jung T. Health risks from combined exposures: mechanistic considerations on deviations from additivity. *Mutat Res*. 1998;411(2):119-128. doi: 10.1016/s1383-5742(98)00011-8.
  21. Jeon J, He X, Shinde A, et al. The role of puff volume in vaping emissions, inhalation risks, and metabolic perturbations: a pilot study. *Sci Rep*. 2024;14(1):18949. doi: 10.1038/s41598-024-69985-1.
  22. Yokoyama A, Muramatsu T, Ohmori T, et al. Esophageal cancer and aldehyde dehydrogenase-2 genotypes in Japanese males. *Cancer Epidemiol Biomarkers Prev*. 1996;5(2):99-102.
  23. International Agency for Research on Cancer (IARC). Allyl Compounds, Aldehydes, Epoxides and Peroxides. In: *IARC Monographs on the Carcinogenic Risk of Chemicals to Humans Volume 36* [Internet]. Lyon: IARC; 1985 [cited 2026 Feb 6]. Available from: <https://publications.iarc.who.int/Book-And-Report-Series/Iarc-Monographs-On-The-Identification-Of-Carcinogenic-Hazards-To-Humans/Allyl-Compounds-Aldehydes-Epoxides-And-Peroxides-1985>
  24. Woutersen RA, Appelman LM, Van Garderen-Hoetmer A, Feron VJ. Inhalation toxicity of acetaldehyde in rats. III. Carcinogenicity study. *Toxicology*. 1986;41(2):213-231. doi: 10.1016/0300-483x(86)90201-5.
  25. Morris JB. Uptake of acetaldehyde vapor and aldehyde dehydrogenase levels in the upper respiratory tracts of the mouse, rat, hamster, and guinea pig. *Fundam Appl Toxicol*. 1997;35(1):91-100. doi: 10.1006/faat.1996.2263
  26. Salem H, Cullumbine H. Inhalation toxicities of some aldehydes. *Toxicol Appl Pharmacol*. 1960;2:183-7. doi: 10.1016/0041-008x(60)90047-8.
  27. Kalapos MP. Methylglyoxal in living organisms: chemistry, biochemistry, toxicology and biological implications. *Toxicol Lett*. 1999;110(3):145-175. doi: 10.1016/s0378-4274(99)00160-5.
  28. Takahashi M, Okamiya H, Furukawa F, et al. Effects of glyoxal and methylglyoxal administration on gastric carcinogenesis in Wistar rats after initiation with N-methyl-N'-nitro-N-nitrosoguanidine. *Carcinogenesis*. 1989;10(10):1925-1927. doi: 10.1093/carcin/10.10.1925.
  29. Marnett LJ, Hurd HK, Hollstein MC, et al. Naturally occurring carbonyl compounds are mutagens in Salmonella tester strain TA104. *Mutat Res*. 1985;148(1-2):25-34. doi: 10.1016/0027-5107(85)90204-0.
  30. Nagao M, Fujita Y, Sugimura T, Kosuge T. Methylglyoxal in beverages and food: its mutagenicity and carcinogenicity. *IARC Sci Publ*. 1986;70:283-291.
  31. Fujioka K, Shibamoto T. Determination of toxic carbonyl compounds in cigarette smoke. *Environ Toxicol*. 2006;21(1):47-54. doi: 10.1002/tox.20153.
  32. St Helen G, Ross KC, Dempsey DA, et al. Nicotine Delivery and Vaping Behavior During ad Libitum E-cigarette Access. *Tob Regul Sci*. 2016;2(4):363-376. doi: 10.18001/TRS.2.4.8.
  33. Shaw IC, Jones HB. Mechanisms of non-genotoxic carcinogenesis. *Trends Pharmacol Sci*. 1994;15(3):89-93. doi: 10.1016/0165-6147(94)90284-4.
  34. van der Toorn M, Slebos DJ, de Bruin HG, et al. Critical role of aldehydes in cigarette smoke-induced acute airway inflammation. *Respir Res*. 2013;14(1):45. doi: 10.1186/1465-9921-14-45.
  35. Ashour AM. Use of Vaping as a Smoking Cessation Aid: A Review of Clinical Trials. *J Multidiscip Healthc*. 2023;16:2137-2144. doi: 10.2147/JMDH.S419945.