Bystander exposure to exhaled e-cigarette vapour: assessment of nicotine in the ambient air using modelling and experimental approaches

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1. Introduction

There is currently a debate on whether the vapour exhaled following the use of e-cigarettes has implications for the quality of air breathed by bystanders. A number of studies have reported that nicotine, amongst other chemical compounds, is exhaled into the air during use of e-cigarettes. A review of the current scientific literature indicates that there is insufficient evidence from which to assess the impact exhaled vapour has on indoor air quality.

Modelling is an important tool for developing and evaluating air quality standards both in terms of airborne concentrations and potential human exposure [1]. Such models are used for assessing compliance with EU Directives on air quality and to assist in the development of evidence based regulation [1].

Models currently exist which can accurately predict indoor air pollutant concentrations measured during conventional cigarette smoking [2].

Here, we developed an air quality model, applying general physical principles, to assess the concentration of nicotine in the ambient air in a simulated office space during use of an e-cigarette ('vaping') to predict human exposure. We then applied this mathematical model to estimate the concentration of nicotine in an indoor environment using input parameters from two recent publications. To test the accuracy of our model, the predictions were compared with published experimental measurements.

2. Air quality modelling: 'single puff profile'

To assess exposure to pollutant concentrations in the ambient air, we considered a number of 'puff phases' during e-cigarette use in our model (**Figure 1A**, *upper panel*). When the e-cigarette user ('vaper') takes a 'puff', the nicotine-containing solution is heated, the vapour is inhaled and a fraction of nicotine is retained by the vaper. The remaining vapour is then exhaled by the vaper where it is propagated and diluted in the ambient air. In this mathematical model, a number of input parameters were considered (**Figure 1A**, *lower panel*).

Following exhalation of a single 'puff', a profile of nicotine concentration in ambient air at the non-vaper's position can be derived from this model (**Figure 1B**).

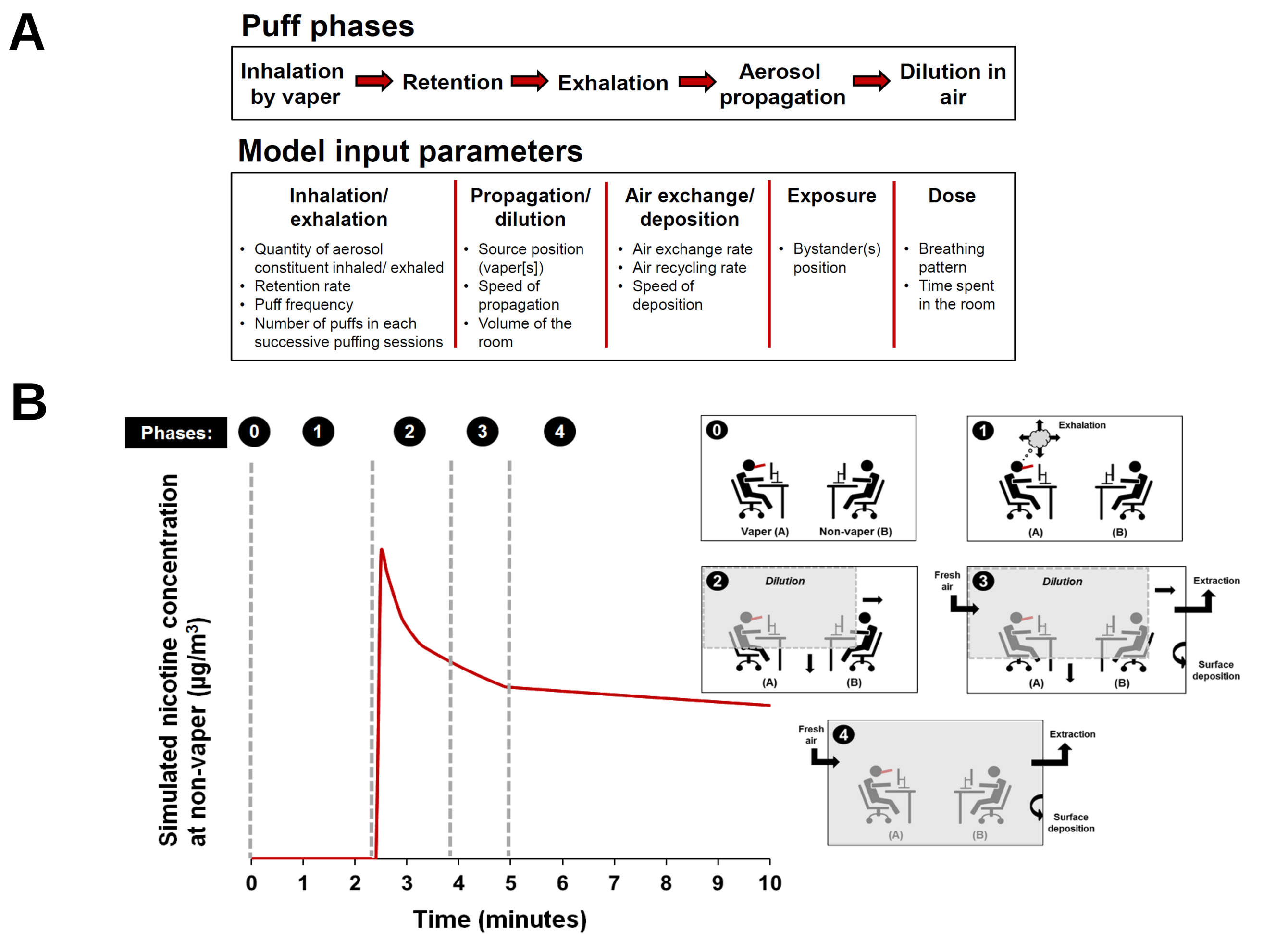

Figure 1 Indoor air quality model to assess exposure to pollutant concentrations in the ambient air during use of an e-cigarette.

(**A**) *Upper panel*, puff phases; *lower panel*, physical input parameters considered in the air quality model.

(**B**) Phases of non-vaper exposure to exhaled vapour after a single 'puff'. *Phase 0*, vaper [A] takes a single 'puff' and inhales the nicotine-containing vapour once every 10 minutes; non-vaper [B] is not exposed to nicotine in the ambient air. *Phase 1*, vaper exhales vapour into the air and it propagates in all directions; non-vaper not yet exposed to nicotine. *Phase 2*, the peak exposure of non-vaper to nicotine in the air is observed corresponding to the time the exhaled vapour reaches the position of the non-vaper; propagation of the exhaled vapour in the indoor air is not yet complete. *Phase 3*, there is a reduction in the concentration of nicotine at the position of the non-vaper due to exhaled vapour propagation and dilution in the air and any surface deposition; it is assumed the air extraction starts when 80% of the room volume is filled with the exhaled vapour. *Phase 4*, there is a reduction in the concentration of nicotine in the ambient air at the non-vaper as the air extraction continues.

3. An illustrative exposure simulation: cumulative nicotine exposure over an 8 hour working day

Here, we considered an office environment scenario, with a non-vaping worker seated 2 metres from a colleague who 'puffs' once every 5 min over an 8 hour period (which includes a 1 hour lunch-break).

In this scenario, we assumed the vaping worker inhales 60 µg of nicotine per 'puff', with 50% nicotine retention; both workers breathe at a rate of 8 L/min [3]. The office is 37 m^3 with a typical air exchange rate of 50 m^3/hr (1.33 times the total room volume per hour); this generates a movement by convection (speed of propagation is 0.6 m/min in all directions), so that each exhaled 'puff' fills the room in 5 min.

We assumed the air extraction effect starts when 80% of the room volume is filled and that no indoor air is recycled after extraction. To maximise nicotine inhaled exposure, the deposition of exhaled vapour onto the surfaces was assumed to be negligible in this scenario.

The cumulative effect of each single 'puff' in the scenario is shown (**Figure 2**).

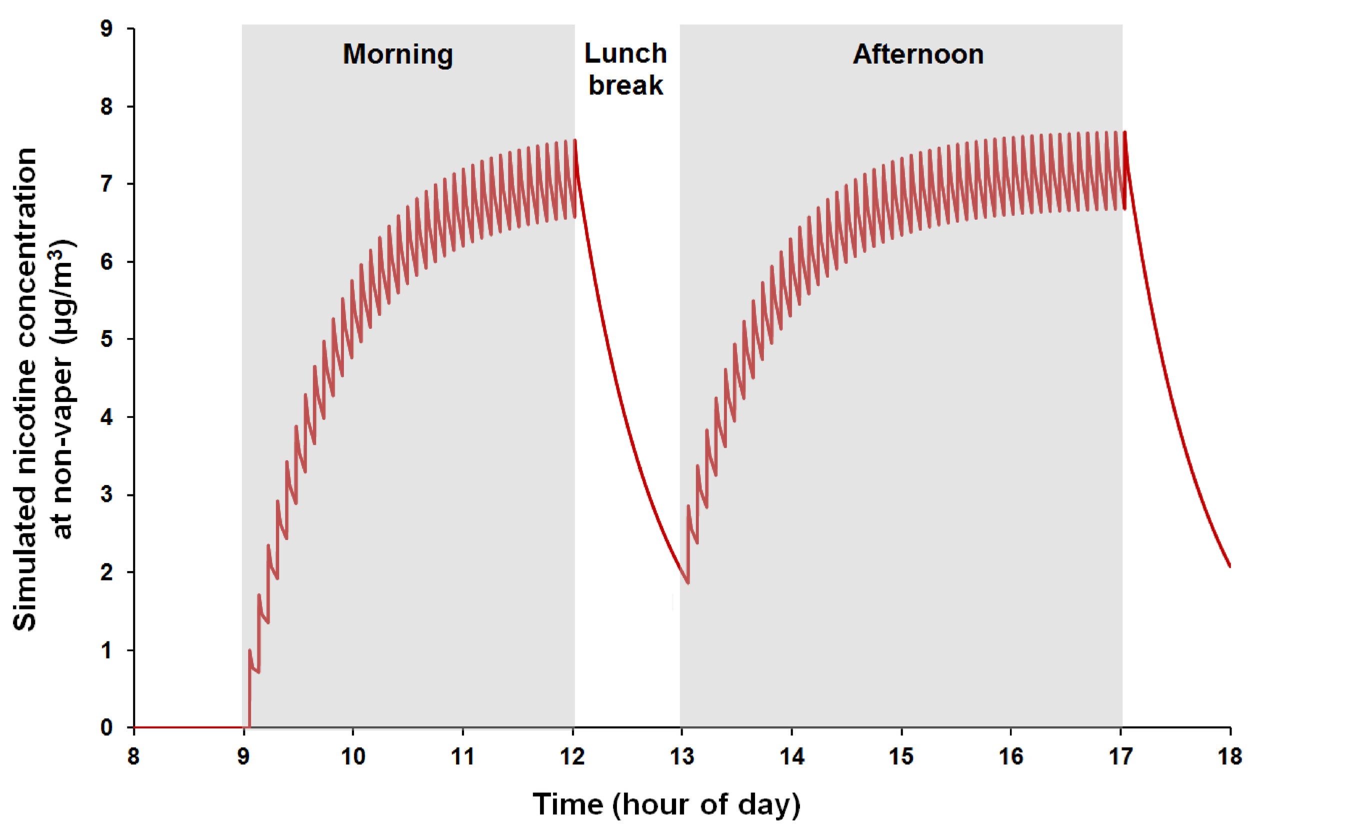

Figure 2 Cumulative effect of each single 'puff' over an 8 hour working day. See text for assumed model input parameters used in this scenario. The concentration of nicotine in the ambient air at the position of the non-vaping worker reaches a maximum when the exhaled vapour emission rate and air extraction rate are equal; in this case, the maximum concentration of nicotine in the ambient air at the position of the non-vaper is approximately 8 $\mu g/m^3$.

In this scenario, we calculated the maximum concentration of nicotine the non-vaping worker is exposed to over the working day is approximately 8 $\mu g/m^3$. The workplace exposure limit for nicotine is 500 $\mu g/m^3$ for average exposure intensity over 8 hours in the workplace [4]. By way of context, the non-vaping worker would need to share this simulated environment of 37 m^3 with 60 vaping workers to reach the workplace exposure limit for nicotine.

Put another way, over the working day, we calculated that the total amount of nicotine potentially inhaled by the non-vaping worker would be approximately 22 µg, equivalent to the nicotine content of 0.012 conventional cigarettes. Accordingly, under this model, a non-vaping worker would need to spend more than 3 months in this office environment scenario to inhale the equivalent amount of nicotine to smoking a single cigarette (as measured by the Canadian intense method).

4. Application of the air quality model

We applied the air quality model to estimate the concentration of nicotine in the indoor ambient air using a matrix of parameters (nicotine delivery, emission pattern and room ventilation) derived from the published literature [5,6]. A total of 12 scenarios were reported in the literature and these were modelled.

Using this information, the air quality model predicted the average 1 hour concentration of nicotine in the air ranged from 1.05 to 20.13 $\mu g/m^3$ (median 4.65 $\mu g/m^3$) across all scenarios [**Figure 3**]. Experimentally, using the same parameters, the average 1 hour concentration of nicotine in the air was reported to range from 0.82 to 6.23 $\mu g/m^3$ (median 2.41 $\mu g/m^3$) (**Figure 3**; [6]).

In this analysis, while the model overestimated nicotine levels in the indoor air environment, values were of the same order of magnitude as the experimental measurements. To confirm the accuracy of model predictions, further experiments are needed to refine and validate the air quality model.

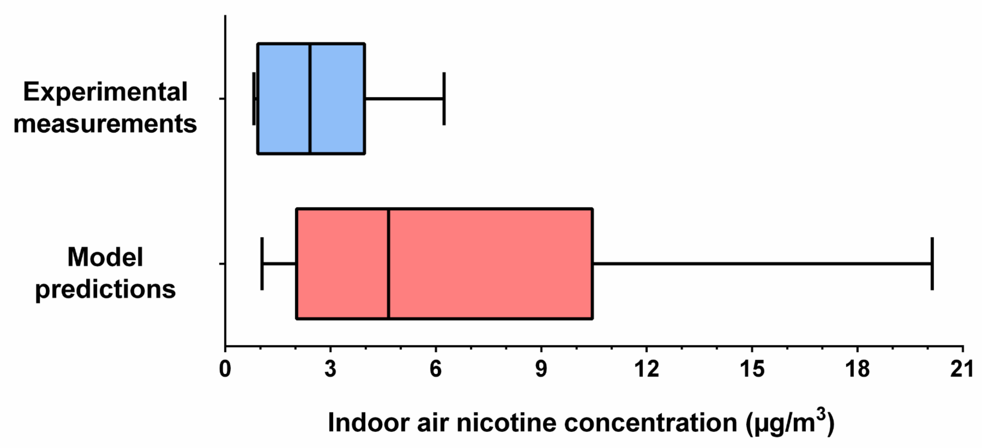

Figure 3 Box plots of the distribution of model predictions and experimental measurements for indoor air nicotine concentration using published experimental parameters [5,6]. A smoking machine, placed in the centre of a 39 m^3 room, was used to generate vapours from e-cigarette products. An air sampling station was located 1 metre from the smoking machine and 10 cm above the level of the e-cigarette product. In this published 1 hour experiment, two doses of vapour were released into the room with a 30 min interval. The model was used to predict the nicotine concentration in air 1 metre from the smoking machine [pink data] when vapours were generated from three e-cigarette products (31 µg, 56 µg and 58 µg nicotine per puff) under two different variants of ventilation ("restricted" [1.37 air changes per hour] and "intensive" [12.6 air changes per hour]) and two variants of emission pattern (low [7 puffs] and high [15 puffs]). Deposition on surfaces was considered negligible in the experimental design. Nicotine retention was consider 0% as vapours released into the room were generated using a smoking machine and not exhaled by human subjects. The experimental measurements reported using this experimental design and parameters [6] are shown (blue data). Boxes represent the 25th and 75th percentiles, lines inside the boxes are medians and whiskers represent minimum and maximum values.

5. Conclusions & future work

The model predictions suggest that under the scenario described, vapour exhaled into the air during use of an e-cigarette product does not produce inhalable exposures to nicotine that would warrant health concerns by the standards that are used to ensure safety of workplaces [4].

The air quality model can be used to predict bystander exposure to other chemical constituents of interest present in exhaled vapour e.g. formaldehyde.

Application of the model using experimentally derived parameters overestimated nicotine concentrations in the indoor air environment and thus bystander exposure when compared to experimental measurements.

Additional refinement of the air quality model is necessary to enable its use as a predictive tool. We now aim to refine and validate the air quality model by:

- determining whether or not experimental results are in agreement with the simulated predictions – we are conducting an experimental study to assess and evaluate the quality of the indoor air before, during and after use of an e-cigarette product in a typical meeting room space under natural ventilation to replicate a 'real-life' scenario;
- calibrating the model input parameters through further experimental studies including quantification of nicotine retention, vaping topography, aerosol propagation speed, surface deposition.

Taken together, appropriately validated models and robust experimental studies may assist in the development of evidence based regulation.

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