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REVIEW
Epidemiology and prevention

Acute cardiovascular effects of electronic cigarettes: a systematic review and meta-analysis

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Electronic cigarette (EC) is widely advertised as a safe alternative to traditional cigarette (TC). We aimed to investigate the cardiovascular effect of EC with/without nicotine compared with TC. We systematically searched PubMed/MEDLINE, EMBASE, and Cochrane CENTRAL for randomized controlled trials that compared the effect of different smoking modalities on cardiovascular function up to 1 October 2024. Analysis used the weighted mean difference (WMD) with a 95% confidence interval (CI) via Comprehensive Meta-Analysis software, version 3.0. The study evaluated key cardiovascular parameters, including pulse wave velocity (PWV), augmentation index at 75 beats/min (AIx75), flow-mediated dilation (FMD), heart rate (HR), systolic blood pressure, and diastolic blood pressure. We analysed 9 trials involving 370 participants. Acute exposure to EC with nicotine (ECN) compared with nicotine-free EC (EC0) increased PWV (WMD = 0.26; 95% CI: 0.14–0.38, $P < 0.001$), AIx75 (WMD = 4.29; 95% CI: 2.07–6.51, $P < 0.001$), and HR (WMD = 5.06; 95% CI: 2.13–7.98, $P = 0.001$), significantly. In contrast, comparison between ECN and TC revealed no significant differences in FMD (WMD = 0.80; 95% CI: −0.09–1.70, $P = 0.08$). Our meta-analysis suggests that ECN acutely increases arterial stiffness more than EC0 does. Additionally, we found that the acute effect of ECN on endothelial dysfunction is not different from TC. Therefore, our study suggests that vaping cannot be considered as a safe substitute for TC. Further investigation is needed to explore the long-term cardiovascular effects of vaping and its modalities.

Keywords E-cigarettes • Cardiovascular function • Pulse wave velocity • Blood pressure • Heart rate • Meta-analysis

Introduction

Electronic nicotine delivery systems, commonly known as electronic cigarette (EC) or vapes, are designed to deliver nicotine as a substitute for traditional cigarette (TC). Although advertisement for EC has claims about safety, cessation-related benefits, and the absence of second-hand smoke, these assertions lack scientific support.[1] Of particular concern, the aerosols produced by EC, commonly referred to as vapour, contain ~47 compounds, several of them are recognized by the Food and Drug Administration as harmful to human health[2] and some are similar to those found in TC. Cigarette smoke contains more than 4000 chemicals, including oxidizing chemicals, carbon monoxide, volatile organic compound, particulates, heavy metals, and nicotine many of them contribute to cardiovascular diseases (CVDs).[3]

Smoking is a potent risk factor for cardiovascular events, CVDs, and cerebrovascular diseases, including coronary heart disease, myocardial

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infarction (MI), stroke, and heart failure.[4] Endothelial has a critical role in cardiovascular health through regulating vascular tone and smoking is recognized as a classic risk factor of endothelial dysfunction. The pathophysiological pathways of smoking involve inflammation, oxidative stress, and atherosclerosis,[5] leading to impaired production of vasoactive compounds. This results in a state of vasoconstriction, pro-inflammatory, and pro-atherothrombotic condition, ultimately impairing blood circulation and disrupting vascular tone regulation.[6] Additionally, atherosclerosis, which is associated with CVD, in its early stages marked by endothelial dysfunction, while in later stages, it is associated with arterial stiffness.[7,8] Increased arterial stiffness and impaired wave reflection is fundamental to decreased aortic velocity and the development of systolic hypertension.[9] Moreover, smoking stimulates sympathetic nervous system, which in turn increases blood pressure (BP) and heart rate (HR).[10,11]

Apart from HR and BP, which are indicators of cardiac haemodynamic state, various markers, including pulse wave velocity (PWV), augmentation index (AIx75), and flow-mediated dilation (FMD), are utilized to assess arterial stiffness, endothelial function, and subclinical atherosclerosis.[12–14] PWV is widely recognized as a simple, non-invasive, and reliable method for assessing arterial stiffness, with higher PWV indicating a more severe atherosclerotic state. It is an established technique with a well-documented association with cardiovascular outcomes.[15,16] Another marker for the assessment of arterial stiffness is AIx75, which is an independent predictor of cardiovascular events and all-cause mortality. AIx75 reflects the interaction between the incident and the reflected pulse wave.[17] On the other hand, quantifying FMD is a non-invasive technique for measuring endothelial function and is an independent predictor of CVD outcomes.[18,19]

The health effects of EC, both the short-term and long-term, remain uncertain, given their relatively recent emergence in the consumer market. Despite these uncertainties, which necessitate caution regarding their safety, it is attracting youth and even former smokers. From 2013 to 2021, the prevalence of current established smokers decreased from 19.6% to 6.1%, while through the same time period, the prevalence of current established vapers increased from 3.8% to 14.5%.[20] Although an epidemiologic study showed that daily vaping is associated with increased risk of MI,[21] a meta-analysis of 20 observational studies found no significant association between EC use and CVD.[22] This inconsistency highlights the need for further research to clarify the effect of vaping on the cardiovascular system. In this study, we investigated the acute effect of vaping on arterial stiffness, endothelial dysfunction, and cardiac physiology by comparing (i) nicotine containing e-cigarettes (ECN) to nicotine-free e-cigarettes (EC0) and (ii) ECN to TC. Additionally, we compared the effect of different smoking modalities on cardiovascular indices at various time points.

Methods

This systematic review and meta-analysis adhered to Preferred Reporting Items for Systematic Reviews and Meta-Analysis statement guideline.[23] The protocol was registered at the International Prospective Register of Systematic Reviews (PROSPERO ID: CRD42023489557) on 15 December 2023.

Data source and search strategy

We thoroughly searched PubMed/MEDLINE, EMBASE, and the Cochrane CENTRAL databases up to 1 October 2024, to identify randomized controlled trials (RCTs) examining the effect of different smoking modalities on cardiovascular functionality markers. The search terms used included 'Electronic Cigarette Vapour', 'E-Cigarette Vapour', 'Electronic Nicotine Delivery System', 'Electronic Cigarettes', 'E-Cig', 'E-Cigarette', 'Electronic Cigarette', 'Vaping', 'Vape', 'Smoking Cessation', 'Electronic tobacco', 'brachial artery', 'vasodilation', 'endothelium', 'vascular', 'endothelial function', 'flow-mediated dilation', 'Vascular Stiffness', 'arterial stiffness', 'arterial compliance', 'arterial distensibility, 'PWV', 'Endothelial progenitor cell', and 'randomized controlled trial'. The complete search strategy is provided in the Supplementary file. Only studies published in English were included.

Study selection

The collected records from the database searches were merged, and duplicates were removed through the utilization of EndNote X7 (Thomson Reuters, Toronto, ON, Canada). Two authors (M.A. and M.C.) conducted a thorough assessment of the records independently, utilizing the title/abstract and full-text screening process to exclude any studies that did not align with the study's eligibility criteria. In case of any discrepancies, a third reviewer (M.J.N.) was involved.

The studies included in the analysis met the following criteria:

(1) Participants: The studies included healthy smokers and non-smokers without a history of CVD and excluded pregnant women.
(2) Intervention: The intervention investigated was the use of ECN.
(3) Comparison: The comparison included the use of EC0 or TC.
(4) Outcome: The primary outcome was the assessment of cardiovascular risk by measurement of PWV and AIx75 as indicators of arterial stiffness, FMD as an indicator of endothelial dysfunction, and HR, systolic blood pressure (SBP), and diastolic blood pressure (DBP) as markers of cardiac physiology.

Data extraction

Two authors (M.A. and M.C.) collaboratively used a structured data extraction form and proceeded to extract information from all included studies. The extracted data encompassed the primary author's name, publication year, study duration, study type, baseline participants' characteristics (e.g. age, sex, and nationality), geographical location(s) of the study, sample size, type of intervention, duration of intervention, concentration of nicotine, and outcomes. Discrepancies were addressed through mutual agreement.

Quality assessment

The assessment of study quality was carried out by two authors (M.A. and M.C.) utilizing the Cochrane Collaboration tool for assessing the risk of bias in RCTs,[24] with any discrepancies resolved by a third reviewer (M.J.N.). This tool covers various domains, including random sequence generation, allocation concealment, blinding of participants and personnel, blinding of outcome assessors, completeness of outcome data, as well as additional considerations such as selective reporting and potential biases.

Data analysis

Three separate analyses were performed. First, we compared the acute effect (immediately to 30 min after exposure) of ECN to EC0 on cardiovascular indices. Second, we compared the acute effect of ECN to TC on cardiovascular indices. Third, we conducted a subgroup analysis, considering several time points including immediately 10, 30, 60, and 120 min after exposure. The statistical analysis was performed using the Comprehensive Meta-Analysis software, version 3.0 (Biostat Inc., Englewood, NJ, USA). The pooled statistic was represented by the weighted mean difference (WMD) accompanied by a corresponding 95% confidence interval (CI). Heterogeneity among the studies was evaluated using the I2 value and *P*-value. In instances of low statistical heterogeneity ($I2 \leq 50\%$ or $P \geq 0.1$), the fixed-effect model was applied. Conversely, when a substantial level of inter-study heterogeneity was observed ($I2 > 50\%$ or $P < 0.1$), the random-effects model was employed. Between-study heterogeneity was assessed using Cochran's Q-test and the I2 statistic. Begg's test was used to evaluate publication bias, with a *P*-value <0.05 considered indicative of statistically significant publication bias.

Results

Figure 1 illustrates the flow diagram of the systematic review process. This thorough review yielded a total of 9 records involving 370 participants who were eligible for our study.[25–33]

As shown in *Table 1*, the included studies cover diverse populations and study designs aimed at comparing the effect of EC0, ECN, and TC on vascular endothelium function. The studies were conducted in

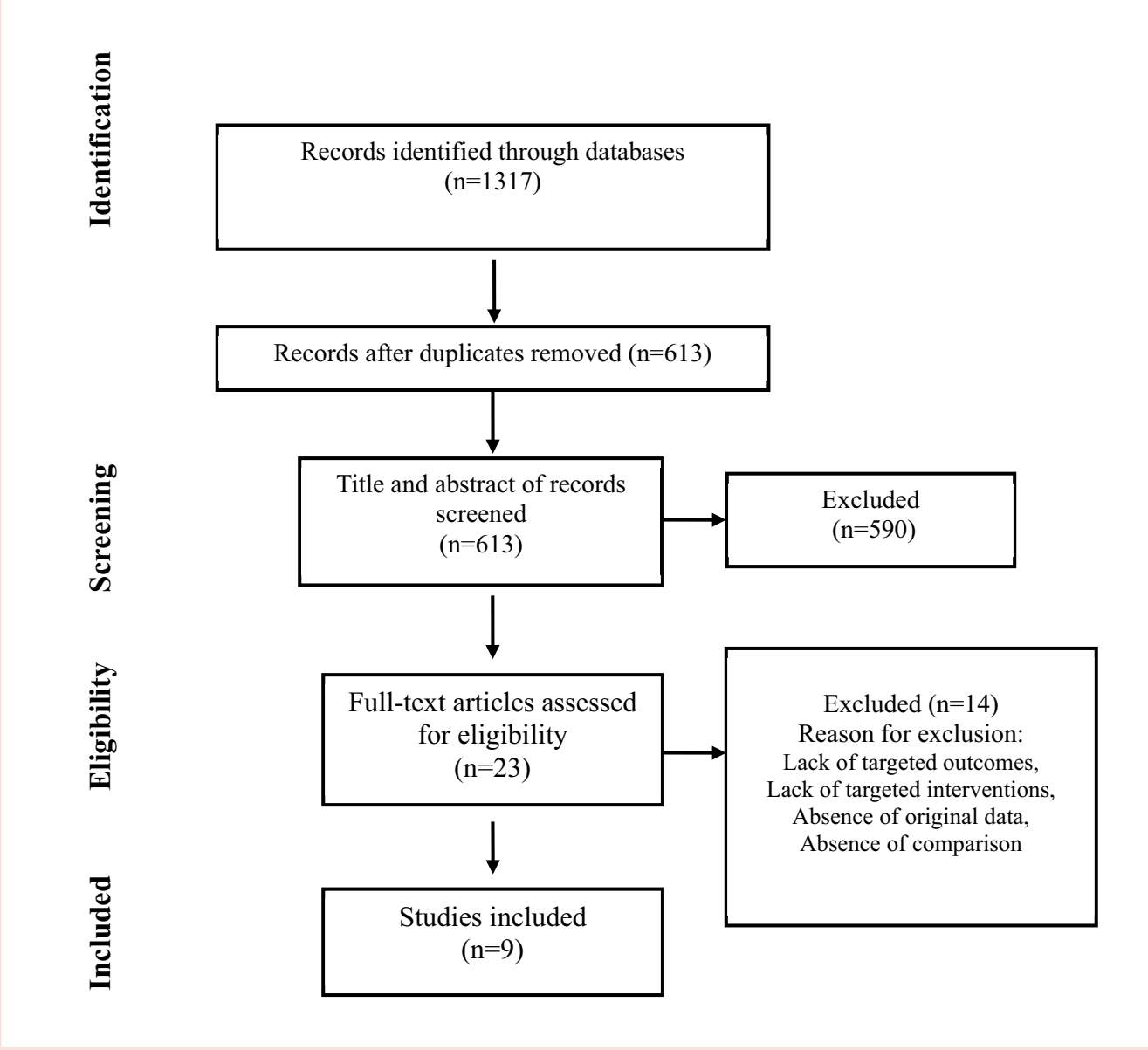

Figure 1 Flow diagram of study selection for inclusion in the systematic review and meta-analysis.

various countries, including the USA, Italy, Greece, Germany, Belgium, and Sweden. The mean ages varied across the studies. Interventions included a range of ECs such as EC fluid with nicotine, EC fluid without nicotine, tobacco-flavoured EC, and second-generation 'pen-like' EC devices, heat-not-burn cigarettes, and third-generation EC. The number of puffs that were consumed varied from 9 to 30 per vaping session. The outcomes focused on comparing the effect of these interventions on endothelial function and arterial stiffness indices including PWV, AIx75, FMD, HR, DBP, and SBP with a time point of assessment ranging from immediately to 120 min after exposure.

Quality assessment

The assessment of the risk of bias is outlined in *Table 2*. Overall, the evaluation of bias across the included studies indicated a generally acceptable methodological rigor. Notably, the study by Carnevale *et al.*,[25] Ikonomidis *et al.*,[27] Antoniewicz *et al.*,[29] Cossio *et al.*,[30] Haptonstall *et al.*,[32] and Lyytinen *et al.*[33] showed higher risks in allocation concealment.

Comparison of the acute effect of electronic cigarette with nicotine to nicotine-free electronic cigarette

Pulse wave velocity

Four studies reported the differential effects of ECN and EC0 on PWV. The assessment time points varied from immediately to 15 min after exposure. Three studies were included in the analysis ($n = 110$). The use of ECN significantly affected PWV levels (WMD = 0.26; 95% CI: 0.14 to 0.38, $P < 0.001$) (*Figure 2*). Additionally, Franzen *et al.*[28] reported that the consumption of ECN resulted in a significant alteration in PWV after 15 min.

Table 1 Characteristics of included studies

Author	Year	Country	Population	Sample size	Age (year) Mean ± SD	Control	Time point of assessment	Design	Wash out period	Nicotine mg/mL
Carnevale *et al.*[25]	2016	Italy	Healthy smoker	20/20	28.0 ± 5.3	TC	30 min	RCD	1 W	16
Carnevale *et al.*[25]	2016	Italy	Non-smoker	20/20	28.0 ± 5.3	TC	30 min	RCD	1 W	16
Chaumont *et al.*[26]	2018	Belgium	Healthy tobacco smokers	25/25	23 ± 0.4	EC0 + Sham vaping	Immediately, 10 min	RCD	1 W	3
Ikonomidis *et al.*[27]	2018	Greece	Healthy current smokers	35/35	48 ± 5	EC0 + Sham vaping	7 min	RCD	60 min	12
Franzen *et al.*[28]	2018	Germany	Healthy current smokers	15/15	22.9 ± 3.5	EC0+ TC	NM	RCD	24 H	24
Antoniewicz *et al.*[29]	2019	Sweden	Healthy occasional users of tobacco products	15/15	26 ± 3	EC0	Immediately, 10 min, 30 min, 2H	RCD	1 W	19
Cossio *et al.*[30]	2019	USA	Healthy tobacco product users	16/16	24 ± 3	EC0	Immediately	RCT	NA	5.4
Biondi-zoccai *et al.*[31]	2019	Italy	Healthy Smokers	20/20	35 ± 13	EC + TC	Immediately	RCD	1 W	NM
Haptonstall *et al.*[32]	2020	USA	Healthy non-smoker	39/41	26.3 ± 5.2	EC0	5 min	RCD	1 W	46.8
Haptonstall *et al.*[32]	2020	USA	Healthy Smoker	23/22	27.4 ± 5.45	EC0	5 min	RCD	1 W	73.5
Lyytinen *et al.*[33]	2023	Sweden	Healthy occasional smokers	22/22	18–45	EC0	30 min, 60 min	RCD	1 W	19

TC, tobacco cigarette; EC, electronic cigarette; EC0, electronic cigarette without nicotine; ECN, electronic cigarette with nicotine; H, hour; mg/mL, milligram per millilitre; min, minute; NA, not applicable; NM, not mentioned; RCD, randomized cross-over design; RCT, randomized clinical trial; TC, traditional cigarette; USA, United States of America; W, week.

Table 2 Quality assessment of the included studies

Author	Year	Random sequence generation	Allocation concealment	Blinding of participants	Blinding of outcome assessors	Incomplete outcome data	Selective reporting	Other bias
Carnevale *et al.*[25]	2016	Low	High	Low	Low	Low	Low	Low
Chaumont *et al.*[26]	2018	Low	Low	Low	Low	Low	Low	Low
Ikonomidis *et al.*[27]	2018	Low	High	High	High	Low	Low	Low
Franzen *et al.*[28]	2018	Low	Low	Low	Low	Low	Low	Low
Antoniewicz *et al.*[29]	2019	Low	High	Low	Low	Low	Low	Low
Cossio *et al.*[30]	2019	Low	High	Low	Low	Low	Low	Low
Biondie-zoccai *et al.*[31]	2019	Low	Low	Low	Low	Low	Low	Low
Haptonstall *et al.*[32]	2020	Low	High	High	High	Low	Low	Low
Lyytinen *et al.*[33]	2023	Low	High	Low	Low	Low	Low	Low

Augmentation index 75

Three studies reported the differential effects of ECN and EC0 on PWV. The time points varied from immediately to 15 min after exposure. All three studies were included in the analysis ($n = 110$). The use of ECN resulted in significant changes in AIx75 levels (WMD = 4.29; 95% CI: 2.07–6.51, $P < 0.001$) compared with EC0 (*Figure 3*).

Flow-mediated dilation

Cossio *et al.*[30] conducted a RCT comparing the effects of ECN to EC0 on FMD. This study suggested no acute effect of ECN compared with EC0 on subclinical vascular function as measured by FMD levels. Haptonstall *et al.*[32] reported no significant difference in FMD before and after exposure to ECN and EC0.

Heart rate

Five studies reported the differential effects of ECN and EC0 on HR. The assessment time points varied from immediately to 30 min after exposure. Three studies were included in the analysis ($n = 107$). The use of ECN significantly changed HR levels (WMD = 5.06; 95% CI: 2.13 to 7.98, $P = 0.001$) (*Figure 4*). Franzen *et al.*[28] and Haptonstall *et al.*[32] reported a notable increase in HR with ECN use.

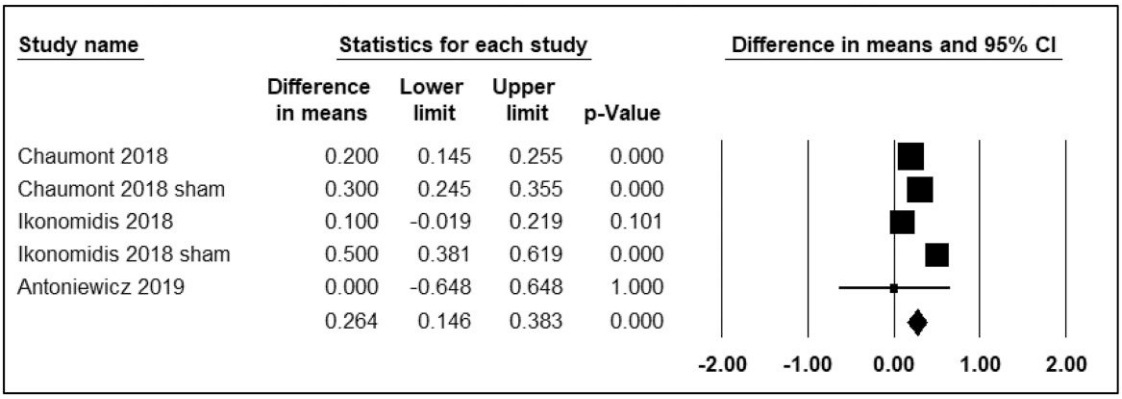

Figure 2 Acute effects of nicotine containing electronic cigarettes on pulse wave velocity, comparison to nicotine-free electronic cigarettes: a random-effect model.

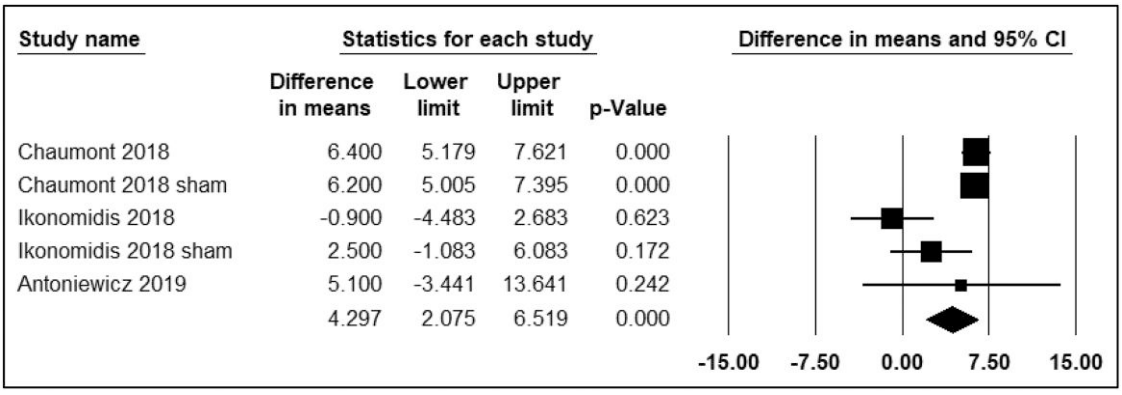

Figure 3 Acute effects of nicotine containing electronic cigarettes on augmentation index 75, comparison to nicotine-free electronic cigarettes: a random-effect model.

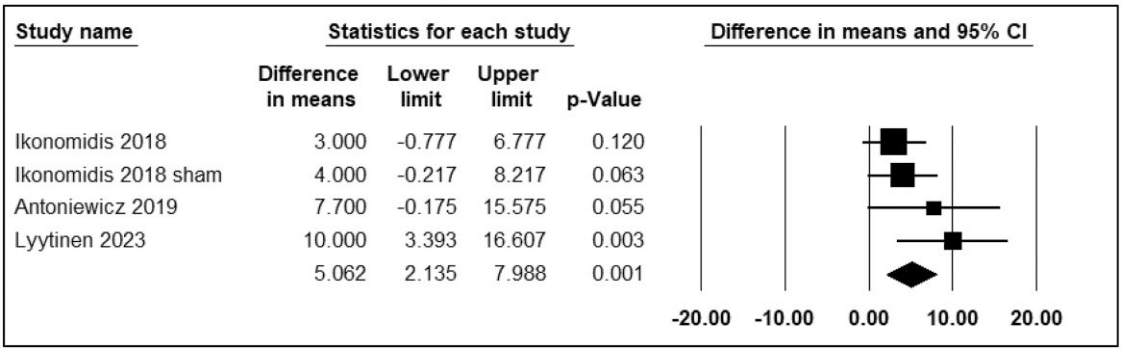

Figure 4 Acute effects of nicotine containing electronic cigarettes on heart rate, comparison to nicotine-free electronic cigarettes: a random-effect model.

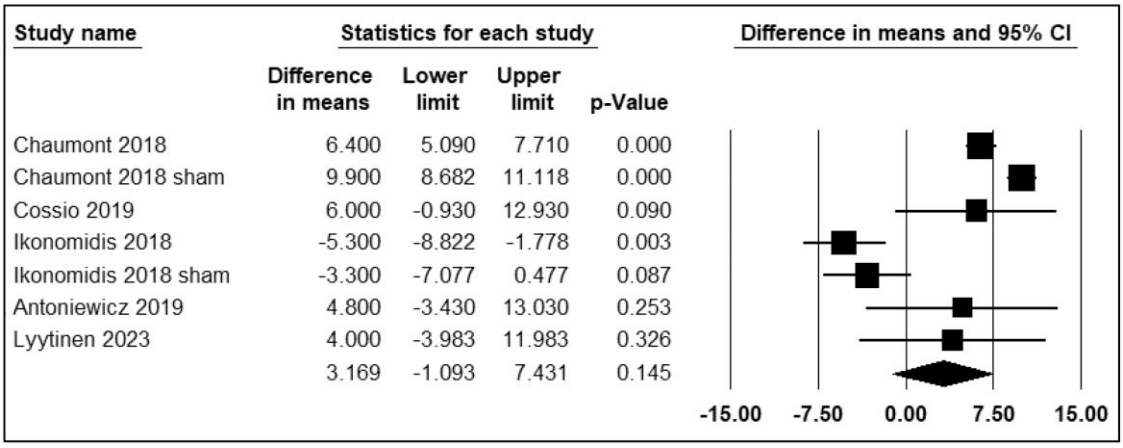

Figure 5 Acute effects of nicotine containing electronic cigarettes on systolic blood pressure, comparison to nicotine-free electronic cigarettes: a random-effect model.

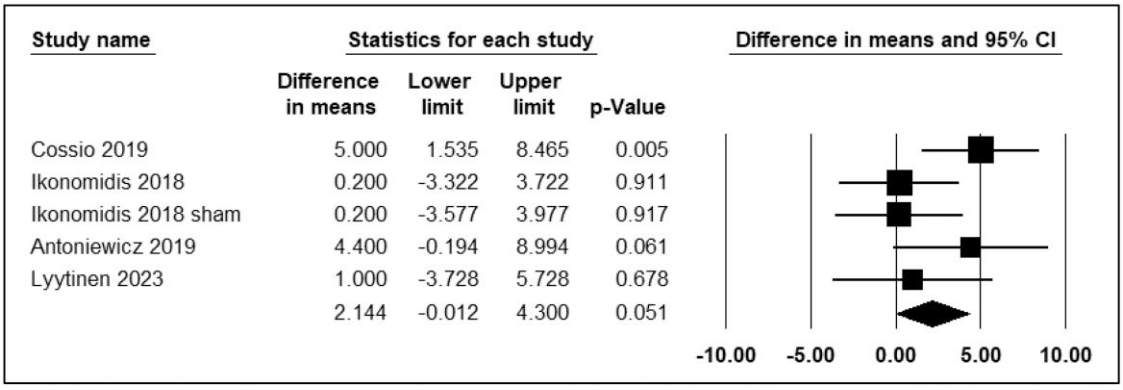

Figure 6 Acute effects of nicotine containing electronic cigarettes on diastolic blood pressure, comparison to nicotine-free electronic cigarettes: a random-effect model.

Systolic blood pressure

Seven studies reported the differential effects of ECN and EC0 on SBP. The assessment time points varied from immediately to 30 min after exposure. Five studies were included in the analysis ($n = 148$). The use of ECN did not result in significant changes in SBP levels (WMD = 3.16; 95% CI: −1.09 to 7.43, $P = 0.14$) (*Figure 5*). However, Franzen *et al.*[28] and Haptonstall *et al.*[32] reported a notable increase in SBP with ECN use.

Diastolic blood pressure

Five studies reported the differential effects of ECN and EC0 on DBP. The assessment time points varied from immediately to 30 min after exposure. Four studies were included in the analysis ($n = 123$). The use of ECN did not result in significant changes in DBP levels (WMD = 2.14; 95% CI: −0.01 to 4.30, $P = 0.05$) (*Figure 6*). However, Haptonstall *et al.*[32] reported a notable increase in DBP with ECN use.

Comparison of the acute effect of electronic cigarette with nicotine and traditional smoking

Two studies compared the effects of ECN and TC on FMD. The assessment time points varied from immediately to 30 min after exposure. The analysis showed that the use of ECN compared with TC did not result in significant changes in FMD levels (WMD = 0.80; 95% CI: −0.09 to 1.70, $P = 0.08$) (*Figure 7*).

Subgroup analysis

In the subgroup analysis, the study population was divided into two distinct groups: ECN and EC0. These groups were analysed separately based on the variables reported in the included studies at various time points, to assess potential differences in their effects over time. The overall results are presented in Supplementary material online, *Table S1*.

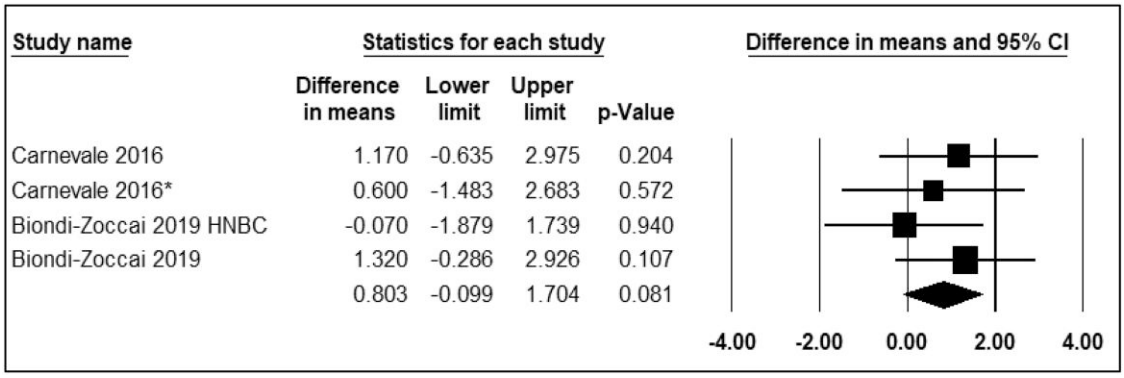

Figure 7 Acute effects of nicotine containing electronic cigarettes on flow-mediated dilation, comparison to traditional cigarettes: a random-effect model.

Comparison of pulse wave velocity, augmentation index at 75 beats/min, and diastolic blood pressure, immediately after exposure to electronic cigarette with nicotine and nicotine-free electronic cigarette

In comparison to EC0, exposure to ECN generally showed a significant increase in PWV (WMD = 0.19; 95% CI: 0.14–0.25, $P < 0.001$), AIx75 (WMD = 6.37; 95% CI: 5.16–7.58, $P < 0.001$), and DBP (WMD = 4.78; 95% CI: 2.01–7.54, $P = 0.001$) immediately after exposure (see Supplementary material online, *Figure S1*).

Comparison of blood pressure, 10 min after exposure to electronic cigarette with nicotine and nicotine-free electronic cigarette

Comparing the effect of ECN to EC0 on SBP revealed no significant difference 10 min after exposure (WMD = 2.10; 95% CI: −7.15–11.36, $P = 0.65$) (see Supplementary material online, *Figure S2*).

Comparison of blood pressure and heart rate, 30 min after exposure to electronic cigarette with nicotine and nicotine-free electronic cigarette

Exposure to ECN compared with EC0 showed no significant difference in SBP (WMD = 4.67; 95% CI: −1.53–10.88, $P = 0.14$) and DBP (WMD = 1.80; 95% CI: −1.63–5.23, $P = 0.30$) after 30 min. However, ECN compared with EC0 increased HR (WMD = 6.84; 95% CI: 0.38–13.30, $P = 0.03$) 30 min after exposure (see Supplementary material online, *Figure S3*).

Comparison of blood pressure, 60 min after exposure to electronic cigarette with nicotine and nicotine-free electronic cigarette

The effects of ECN and EC0 on SBP (WMD = −0.36; 95% CI: −4.99–4.26, $P = 0.87$) and DBP (WMD = 0.21; 95% CI: −2.76–3.19, $P = 0.88$) showed no significant difference 60 min after exposure (see Supplementary material online, *Figure S4*).

Comparison of systolic blood pressure, 120 min after exposure to electronic cigarette with nicotine and nicotine-free electronic cigarette

The effects of ECN and EC0 on SBP, 120 min after exposure, revealed no significant difference (WMD = 2.04; 95% CI: −2.83–6.92, $P = 0.41$) (see Supplementary material online, *Figure S5*).

Comparison of FMD 30 min after exposure to electronic cigarette with nicotine and traditional cigarette

When comparing the effect of ECN to TC, there was no notable difference in FMD 30 min after exposure (WMD = 0.92; 95% CI: −0.43–2.29, $P = 0.18$) (see Supplementary material online, *Figure S6*).

Discussion

Our systematic review and meta-analysis includes 9 clinical trials with a total of 370 subjects, aimed at comparing the effect of ECN to EC0 and ECN to TC on cardiovascular indices. Our findings indicate that the acute effect of ECN compared with EC0 is an elevation in PWV, AIx75, and HR, while the acute effect of ECN on endothelial dysfunction is not different from TC. Additionally, vaping ECN may result in an immediate increase in PWV, AIx75, and DBP, which compared with EC0 is significant. The mean differences in other parameters were not statistically significant.

Previous studies reported that tobacco smoking is a determinant of CVDs and increases the risk of cardiovascular events, including acute MI, sudden cardiac death, and stroke.[34] The adverse effect of smoking on endothelial dysfunction, throughout all phases of atherosclerosis has been widely studied.[35] Exposure to tobacco smoke impacts various components of the haemostatic process, including endothelial cells, platelets, fibrinogen, and coagulation factors.[36] This initiates vascular dysfunction by reducing nitric oxide (NO) availability and increasing the expression of adhesion molecules, resulting in endothelial dysfunction. Furthermore, smoking promotes tissue remodelling, pro-thrombotic activity, and systemic inflammation, all of which contribute to atherogenic changes in the vessel wall.[37] One common component of both EC and TC is nicotine. Of great notice is that, when interpreting results from experimental studies comparing the effects caused by TC and EC, several elements should be considered. First, differences in nicotine blood level concentration depend on the rate and pattern of consumption. A study by D'Ruiz *et al.* showed that EC use, compared with TC, delivers the same amount of nicotine but with slower absorption.[38] Second, nicotine receptors undergo desensitization and develop tolerance, which is important to consider when evaluating the outcome of acute experimental exposure. The effects of a single, short-term exposure might differ from those seen with prolonged exposure in regular TC or EC users.[39]

Flow-mediated dilatation, pulse wave velocity, and augmentation Index 75

Endothelial dysfunction is a valuable indicator for cardiovascular risk and is known as a key feature of early stage systemic atherosclerosis.[25]

Markers such as FMD, PWV, and AIx75 are commonly used to assess vascular function, though each may be best suited to specific conditions or reflect specific abnormalities. Results of a meta-analysis by Witte *et al.* found that FMD is associated with cardiovascular risk factors only in low risk populations.[40] Meanwhile, McEniery *et al.* suggested that AIx may be more sensitive in younger adults; whereas, PWV serves as a more reliable indicator in elderly.[41] Our analysis did not find a significant difference in the FMD impairment after acute exposure to either ECN compared with EC0, or ECN compared with TC. Since FMD is more reflective of chronic smoking exposure,[42] this lack of difference may indicate that the acute effects of these smoking modalities on vascular endothelial function are comparable in the short-term. The findings of our study are supported by a meta-analysis conducted by Meng *et al.*,[43] which included four studies and similarly reported no significant difference in FMD when comparing the acute effects of EC to TC. A pathway through which nicotine impacts cardiovascular health is by inactivation and reducing the bioavailability of NO, a critical molecule for vessel dilation. This reduction in NO leads to a decrease in FMD, which has been observed in both TC and EC users.[25]

Yufu *et al.* demonstrated that smokers experience a reduction in FMD, which could be anticipated by an increase in PWV.[44] In a healthy vascular system, the pulse wave returns to the heart during diastole, supporting coronary blood flow. However, in a stiffened vascular system, PWV is elevated, causing the wave to return to the heart pre-maturely during systole. This early reflection increases cardiac afterload and reduces diastolic augmentation, impairing coronary perfusion.[45] Saz-Lara *et al.* in their systematic review and meta-analysis focused on the effect of smoking, vaping, and smoking cessation on arterial stiffness. They calculated the pooled effect size using the standardized mean difference and showed an increase in PWV after smoking cessation, which was equal to a moderate reduction in arterial stiffness. Moreover, their results demonstrated that both traditional smoking and vaping significantly increased the PWV.[46] Similar findings were reported in the clinical trial by Franzen *et al.*[28] which showed an increase in AIx75 and PWV, 15 min after exposure to ECN. Our results further confirm these findings, demonstrating that ECN, compared with EC0, results in a more pronounced immediate increase in PWV and AIx75, although both ECN and EC0 contribute to an elevation in these vascular markers. Additionally, our results showed that exposure to ECN compared with EC0 may result in the acute elevation of PWV and AIx75.

Heart rate, systolic blood pressure, and diastolic blood pressure

Vlachopoulos *et al.* compared the effects of EC and TC on blood pressure and found that both EC and TC significantly increased SBP and DBP, with no significant difference between the two in the magnitude of these changes.[47] Skotsimara *et al.* in their meta-analysis included three studies and showed that switching from TC to EC did not affect HR; however, it reduced both SBP and DBP.[48] Our results showed that vaping ECN compared with EC0 may lead to a greater increase in DBP, immediately after exposure, and an elevation in HR, 30 min after exposure. The difference in findings of the two studies may be related to different time points. Nicotine typically stimulates the sympathetic nervous system, leading to elevated BP and HR. However, nicotine's effect on coronary blood flow is more complex and can even be contradictory. While nicotine reduces coronary blood flow by constricting coronary arteries, it can also increase cardiac output, which naturally leads to coronary artery dilation and an increase in blood flow. The net effect depends on the balance between these opposing actions, often resulting in a less-than-expected increase in blood flow to the heart muscle.[39] Mueller *et al.* compared the effect of vaping and TC on cardiovascular response and showed that nicotine consumption, regardless of the method of use, has an acute dose-dependent effect on both blood pressure and HR. They argued that since vapers tend to consume nicotine more frequently, they may exhibit an enhanced cardiovascular response,[49] which may persist and intensify throughout the day, as vapours have fewer rest periods between nicotine intake.

Our study has several notable strengths. Unlike previous meta-analysis studies, our systematic review and meta-analysis extended the comparison to include EC0, ECN, and TC, while evaluating a broader range of cardiovascular parameters including PWV, AIx75, and FMD, HR, SBP, and DBP. Furthermore, our study incorporated data from multiple time points (immediately, 10 min, 30 min, 60 min, and 120 min after exposure), providing a comprehensive understanding of the temporal dynamics of the observed effects. However, the number of studies assessing outcomes at longer time intervals remains limited, highlighting the need for further investigation into the long-term cardiovascular effects of ECs and their impact on cardiovascular event risk over extended periods. On the other hand, our study faced several limitations. First, variability in participant characteristics across the included studies may contribute to heterogeneity, potentially affecting the generalizability of our findings. Second, lack of long-term follow-up data limits our ability to evaluate the sustained effects of EC use on vascular parameters, necessitating caution when extrapolating our results to chronic exposure scenarios. Third, the wide variety of EC products introduces complexity in assessing their collective impact, as the specific constituents of ECN and EC0 may vary between brands, potentially influencing the observed outcomes.

In conclusion, based on the results of our comprehensive systematic review and meta-analysis, e-cigarette with nicotine may cause arterial stiffness immediately after exposure, suggesting potential cardiovascular event risks, which is greater than the effect of e-cigarette without nicotine. The results of our study found that the effect of e-cigarette with nicotine on FMD is comparable with TC. Given the evidence of acute cardiovascular effects associated with e-cigarette use, promoting vaping as a safe alternative to traditional smoking is not supported by current data and warrants serious reconsideration.

Lead author biography

Dr. Mehdi Mirsaeidi, M.D., M.P.H., is a Professor of Medicine and Chief of Pulmonary, Critical Care, and Sleep Medicine at the University of Florida College of Medicine in Jacksonville. His research centres on respiratory diseases and the health impacts of environmental exposures, including tobacco and vaping. Dr. Mirsaeidi's lab investigates the acute and chronic effects of vaping on respiratory and cardiovascular health, providing critical insights into its role in disease exacerbation. His team has demonstrated that vaping increases the risk of pulmonary infections and induces inflammation in bronchial epithelial cells, advancing understanding of its harmful effects.

Data availability

The data used to support the findings of this study are included within the article.

Supplementary material

Supplementary material is available at *European Heart Journal Open* online.

Authors' contribution

All authors contributed equally to this work.

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