

1 **Research article**
2 **Pulmonary toxicity and inflammatory response of**
3 **e-cigarettes containing medium-chain triglyceride oil**
4 **and vitamin E acetate: Implications in the**
5 **pathogenesis of EVALI but independent of**
6 **SARS-COV-2 COVID-19 related proteins**

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15 **Abstract:** Recently, there has been an outbreak associated with the use of e-cigarette or vaping
16 products, associated lung injury (EVALI). The primary components of vaping products, vitamin E
17 acetate (VEA) and medium-chain triglycerides (MCT) may be responsible for acute lung toxicity.
18 Currently, little information is available on the physiological and biological effects of exposure to
19 these products. We hypothesized that these e-cig cartridges and their constituents (VEA and MCT)
20 induce pulmonary toxicity, mediated by oxidative damage and inflammatory responses, leading to
21 acute lung injury. We studied the potential mechanisms of cartridge aerosol induced
22 inflammatory response by evaluating the generation of reactive oxygen species by MCT, VEA, and
23 cartridges, and their effects on the inflammatory state of pulmonary epithelium and immune cells
24 both in vitro and in vivo. Cells exposed to these aerosols generated reactive oxygen species, caused
25 cytotoxicity, induced epithelial barrier dysfunction, and elicited an inflammatory response. Using a
26 murine model, the parameters of acute toxicity to aerosol inhalation were assessed. Infiltration of
27 neutrophils and lymphocytes was accompanied by significant increases in IL-6, eotaxin, and G-CSF
28 in the bronchoalveolar lavage fluid (BALF). In mouse plasma, eicosanoid inflammatory mediators,
29 leukotrienes, were significantly increased. Plasma from e-cig users also showed increased levels of
30 hydroxyeicosatetraenoic acid (HETEs) and various eicosanoids. Exposure to e-cig cartridge
31 aerosols showed the most significant effects and toxicity compared to MCT and VEA. In addition,
32 we determined at SARS-COV-2 related proteins and found no impact associated with aerosol
33 exposures from these tested cartridges. Overall, this study demonstrates acute exposure to specific
34 e-cig cartridges induces in vitro cytotoxicity, barrier dysfunction, and inflammation and in vivo
35 mouse exposure induces acute inflammation with elevated pro-inflammatory markers in the
36 pathogenesis of EVALI.

37 **Keywords:** EVALI, E-cigarettes, oxidative stress, Inflammation, Barrier Dysfunction, MCT, VEA
38

39 1. Introduction

40 Electronic Nicotine Delivery Systems (ENDS) products are battery-operated devices equipped
41 with a tank, cartridge, or a pod filled with a liquid (e-liquid). These e-liquids may contain a base
42 liquid (humectant), such as propylene glycol (PG) and vegetable glycerin (VG). Other contents
43 include nicotine, flavoring chemicals, and flavor enhancers. Recently, cartridges containing
44 tetrahydrocannabinol (THC) and cannabidiol (CBD) have been introduced to the ENDS market.
45 These cartridges predominantly use carriers such as mineral oil and medium-chain triglycerides
46 (MCT) oil. The heating element in these cartridges, i.e., coil/atomizer, raises the temperature of the
47 e-liquid or oil to aerosolize its constituents. Some of these products have become abundantly
48 available in the market containing adulterants, such as butane hash oil (a.k.a dabs) [1]. Using these
49 products has caused acute lung injury to many e-cigarette (e-cig) users and the disease was
50 recognized as e-cigarette, or vaping, associated lung injury (EVALI) in August 2019. As of February
51 2020, a total of 2807 hospitalized cases or deaths have associated with EVALI, according to the
52 Centers for Disease Control and Prevention [2]. Symptoms of EVALI include labored breathing,
53 dyspnea, chest pain, cough, nausea, diarrhea, fatigue, fever, and weight loss [3,4].

54 All EVALI patients have a history of e-cigarette use or vaping and the majority report using THC
55 containing vaping products. No single constituent has been identified as the causative agent of
56 EVALI. However, vitamin E acetate has been found in bronchoalveolar lavage fluid (BALF) of
57 EVALI patients [5]. Most of the subsequent analyses have been geared towards the constituents of
58 e-liquids like Vitamin-E acetate (VEA) as implicated in these ENDS-user subjects [6-8]. There is an
59 urgent need for experimental-based studies to implicate the causative role of VEA in EVALI or other
60 lung conditions reported. There is a gap in research and knowledge of pulmonary effects and vaping
61 mediated toxicity. Additionally, inhalation toxicology studies *in vitro* and *in vivo* are needed to
62 investigate the effects of exposure to constituents of e-liquids and vaping cartridges.

63 In this study, we provide the mechanisms of toxicity of inhalation exposure to e-cig cartridges and
64 their major components. We assessed the total volatile organic compounds in the aerosols and
65 conducted an *in vitro* toxicity assessment using lung epithelial cells and monocytes. The parameters
66 of *in vitro* toxicity assessment included cell viability, ROS generation, trans-epithelial barrier
67 function, and inflammatory mediators. To assess the acute inhalation toxicity of MCT, VEA, and
68 e-cig cartridge aerosols *in vivo*, an acute exposure mouse model was utilized. In these exposed
69 mouse groups, immune cell influx and cytokines in BALF were quantified to investigate the elicited
70 inflammatory response compared to the unexposed counterparts. In addition, we studied at
71 SARS-COV-2 related proteins and found no impact associated with aerosol exposures from these
72 tested cartridges. We demonstrated a reduction in surfactant protein A in lung homogenates of VEA
73 exposed mice, which plays a role in lipid homeostasis and innate immune defense. Lipidomics
74 analyses performed on BALF of mice exposed to MCT, VEA, and e-cig cartridge aerosols, as well as
75 plasma of e-cig users, showed changes in eicosanoids and, exhibiting their role in pulmonary
76 inflammation. Further, we found altered glycerolipids, cholesterol esters, and glycerophospholipids
77 in mouse BALF upon acute VEA and cartridge exposure. We hypothesized that VEA, MCT, and
78 other chemical constituents present in e-cigarette cartridges [9] cause cellular toxicity, and oxidative
79 and inflammatory responses in epithelial cells, monocytes, and *in vivo* in mouse lung upon
80 inhalation.

81

82 2. Material and Methods

83 2.1 Scientific rigor and reproducibility

84 We have applied robust unbiased experimental design and data analysis approaches
85 throughout the study. We have validated the methods and ensured reproducibility with repeated
86 experiments. All methods are presented in detail with transparency. Results were reported and
87 interpreted without bias. Laboratory grade biological and chemical resources were purchased from
88 commercial sources. Our methodologies, data, and results adhered to strict NIH standards of
89 reproducibility and scientific rigor.

90 **2.2 Ethics statement: Institutional biosafety and animal protocol approval.**

91 Experiments in this study were performed according to the standards and guidelines approved
92 by The University of Rochester Institutional Biosafety Committee (Study approval
93 #Rahman/102054/09-167/07-186; identification code: 07-186; date of approval: 01/05/2019 and
94 02/03/2020). Validated cell lines, human bronchial epithelial cell lines (16-HBE and BEAS2B) and
95 human monocytic leukemia derived cell line (MONO-MAC-6), were procured from ATCC, USA.
96 Ethical approval was not necessary for the utilized cell lines.

97 All mouse housing, handling, exposure, and procedure protocols used in this study were
98 approved by the University Committee on Animal Research (UCAR) Committee of the University of
99 Rochester, Rochester, NY (UCAR protocol 102204/UCAR-2007-070E, date of approval: 01/05/2019
100 and 02/03/2020).

101 Human plasma samples used for lipidomics analysis were from the study conducted at the
102 University of Rochester Medical Center (Rochester, NY, USA) (Institutional Review Board approval
103 RSRB00064337) [10].

104 **2.3 Aerosol exposure setup**

105 An Ooze slim twist vaping pen set at 3.8V was connected to the Scireq Inexpose pump
106 (Montreal, Canada). For in vitro exposures, cell culture plates were placed inside an EnzyScreen
107 chamber (EnzyScreen BV, Netherlands) and exposed to two 70 mL puffs of the aerosol under
108 air-liquid interface conditions. The cells were allowed to incubate in the vapor for 10-minutes.

109 For in vivo exposures, wild type mice with C57BL/6 background were exposed to 1 hr MCT,
110 VEA, and cartridge aerosols with 70 mL puffs, two puffs/min using the Scireq Inexpose system
111 (Montreal, Canada) [11].

112 **2.4 Vitamin E acetate (VEA) 50% w/v preparation**

113 A refillable vape oil cartridge was filled with either MCT oil (GreenIVe, Amazon) or tocopherol
114 acetate (Sigma Cat# PHR1030-500MG) was mixed with MCT oil to make a 50% w/v or 1.06 M VEA.

115 **2.5 E-cigarette cartridges**

116 For the cell and mouse exposures in this study, e-cig cartridges used in our previous study
117 characterizing constituents of EVALI were used [9].

118 **2.6 Physicochemical characteristics of MCT and VEA**

119 Respirable particle concentration and distribution:

120 Dusttrack II aerosol monitor 8530 (TSI, MN) was used to measure respirable particles with
121 aerodynamic diameter 1.0, 2.5, 4.0, and 10.0 μm by taking readings immediately after a single puff
122 was released to a chamber with dimensions 8" x 6" x 5.25" (EnzyScreen, Netherlands). Data collection

123 duration is one minute with a 10s moving average. These fine particle measurements were obtained
124 for air, MCT, VEA, and e-cig cartridge aerosols.

125

126 **2.7 Measurement of total volatile organic compounds (VOC) levels in aerosols**

127 To measure the VOC levels inside the EnzyScreen chamber, the exhaust tubing was connected
128 to a 50 mL conical tube. A photoionization detector probe 985 (TSI, MN) was placed inside the
129 conical tube, and the total VOC levels in air, MCT, VEA, and cartridge aerosols were recorded.

130

131 **2.8 Acellular ROS Assay**

132 Cell-free ROS generated by MCT, VEA, and e-cig cartridge aerosols were determined using
133 2',7'-dichlorofluorescein diacetate (H₂-DCF-DA) fluorogenic probe (Sigma-Aldrich Cat# 287810).
134 H₂-DCF-DA [5 mM] with NaOH [0.01N] was reacted for 30 minutes to prepare the dye. After
135 incubation, 25 mM phosphate buffer was added to stop the reaction followed by the addition of 2
136 mL HRP. A set of hydrogen peroxide standards ranging from 0 to 50 μ M was prepared from a 1M
137 H₂O₂ stock. Subsequently, two puffs of MCT, VEA, and e-cig cartridges were bubbled through an
138 impinger containing 10 mL of the dye connected to Scireq Inexpose pump. After aerosolization, the
139 samples were incubated for 15 minutes at 37 °C in a water bath. Subsequently, the
140 absorbance/emission was read at 485/535 nm with Turner Quantech fluorometer (FM109535,
141 Barnstead international).

142

143 **2.9 Cellular ROS Assay**

144 2',7'-dichlorofluorescein diacetate (H₂-DCF-DA) fluorogenic probe (Sigma-Aldrich Cat# 287810)
145 dye was prepared as described. 15,000 BEAS-2B cells/well were cultured in a 96-well plate in
146 complete medium to 80% confluency. After serum depriving the cells at 1% FBS for 12 hours, 20 μ M
147 dye was added to each well of the 96-well plate and was incubated for 30 minutes. After incubation,
148 the cells were treated with 0.25% (v/v) MCT, and 0.025% (w/v) or 50 μ M VEA, and a mixture of e-cig
149 cartridge liquids at 0.0001% (v/v). The absorbance/emission was read at 485/535 nm at 1.5 hours, 4
150 hours, and 6 hours using microplate spectrophotometer (Cytation 5, Biotek).

151

152 **2.10 Cell Culture**

153 Bronchial epithelial cells, BEAS-2B, were cultured in DMEM F-12 50/50 base media and
154 supplemented with 5% FBS, 1% Pen/Strep, and HEPES. Cells were plated at 300,00 cells/well in 6
155 well plates in complete medium. At 80% confluency, the cells were serum-deprived in 1% FBS.
156 Similarly, epithelial cells, 16-HBE, were cultured in DMEM base media and supplemented with 1%
157 Pen/Strep, 10% FBS, and 1ml Amphotericin B. 16-HBE cells were plated and serum-deprived in 1%
158 FBS. Monocytes, Mono-Mac-6 (MM6), were cultured in 24-well culture plates in RPMI 1640 media
159 and supplemented with 1% Pen/Strep, 1mM Sodium Pyruvate, 2mM L-glutamine, non-essential
160 amino acid, Transferrin, Oxaloacetic acid, Polymixin B, and Bovine Insulin. At 80% confluency,
161 MM6 cells were serum-deprived in 1% FBS 12-hours before treatment.

162

163 **2.11 Aerosol exposures and treatments to cells**

164 Epithelial cells (BEAS-2B and 16-HBE) were exposed to MCT, VEA (50% w/v), and e-cig
165 cartridges, as described in the exposure setup section. Twenty-four hours post-exposure, the
166 conditioned media, and the cell pellets were collected for further analysis.

167 Monocytes, MM6 cells were treated with %0.25 (v/v) MCT, 0.025% (w/v) or 50 μ M, and 0.0001%
168 cartridges in 1% FBS media. Twenty-four hours later, conditioned media and cell pellets were
169 collected.

170

171 **2.12 Cytotoxicity Assay**

172 To assess the induced cytotoxicity by MCT and VEA treatments, 20 μ L of cells were mixed with
173 20 μ L of Acridine Orange/Propidium Iodide. Then, 20 μ L of the mixture was added to the Nexcelom
174 automated cell counter slide, and viability and the live and total cell counts were performed using a
175 Nexcelom 2000 Cellometer (Nexcelom Bioscience, Lawrence MA).

176

177 **2.13 Cytokine ELISA**

178 Conditioned media collected from each well was used to determine inflammatory cytokine
179 release. Interleukin 6 (IL-6) was measured using an IL-6 ELISA kit following manufacturer's
180 instruction (Invitrogen, Catalog # CHC1263). Similarly, an interleukin-8 (IL-8) ELISA kit (Invitrogen,
181 Catalog # CHC1303) to quantify secreted IL-8 levels in conditioned media. The cartridge aerosol
182 exposed data points were then pooled, and the average was compared with air, MCT, and VEA.

183

184 **2.14 Trans-epithelial electrical resistance (TEER) measurement**

185 16-HBE cells (20,000 cells/well) were cultured on 24-well transwell inserts (Corning cat# 3470)
186 until the cells reached a complete monolayer. Cells were then serum-deprived at 1% FBS 12-hours
187 before exposure. Cells were exposed to MCT, VEA, and cartridge aerosols using the previously
188 described aerosol exposure setup. 24-hours later, the barrier function was evaluated by recording
189 the transepithelial voltage and resistance by EVOM2 (WPI instruments, FL). Each well was
190 measured three times, and the average unit area resistance was calculated. Cartridge aerosol
191 exposed data points were then pooled, and the average was compared with the unexposed air
192 group.

193

194 **2.15 In vivo mouse exposures**

195 Approximately four month old male and female mice with C57BL/6 background were exposed
196 to medium-chain triglyceride oil (MCT), vitamin E acetate (50% w/v in MCT), and e-cig cartridge
197 aerosols one-hour per day for three consecutive days, as described in the aerosol exposure setup
198 section [11]. For cartridge aerosols, six different cartridges were aerosolized for 10-minute cycles.
199 Immediately following the last exposure, mice were euthanized and the tissues were collected.

200

201 **2.16 Mouse arterial oxygen saturation**

202 Immediately prior to mouse euthanasia, arterial oxygen saturation was measured in mice by
203 MouseOX plus device (STARR life science, PA). Data collected over approximately ~8 minutes and
204 any unstable data points were removed, including the first 60s.

205

206 **2.16 Bronchoalveolar lavage (BALF) collection**

207 Upon anesthesia 0.6 mL of 0.9% NaCl saline solution was instilled three times (1.8 mLs
208 cumulative volume) into the trachea and the recovered BALF centrifuged at 1000 RPM for 7 minutes.
209 The acellular fraction of the BALF was stored at -80°C for cytokine analysis by Luminex assay. The
210 pelleted cells were then used for flow cytometry analysis to obtain differential cell counts.

211

212 **2.17 Luminex assay**

213 To determine inflammatory mediators released due to MCT, VEA, and e-cig cartridge aerosol
214 exposures, 50 µL of the BALF sample was used with BioRad 23-plex-Group I kit (BioRad Cat#
215 M60009RDPD) according to the manufacturer's instructions. Briefly, capture antibody coupled
216 magnetic beads were added to the plate, followed by the addition of samples and the standards.
217 After incubating, detection antibody and streptavidin-PE were added. The appropriate number of
218 washing steps and incubation steps were followed as instructed. After resuspending the sample in
219 125 µL of assay buffer, the plate was read on a FLEXMAP 3D system (Luminex). The concentrations
220 of each analyte were compared to the unexposed air group and the analytes that showed significant
221 differences were reported.

222

223 **2.18 Flow cytometry analysis**

224 Collected cells from the BALF recovery were counted by AO/PI assay to obtain total cell counts.
225 The cells were then blocked with anti-CD16/32 (Fc block) for 10 minutes. Followed by a PBS wash
226 step, cells were stained with CD45, F4/80, Ly6B.2, CD4, and CD8 cell surface markers in staining
227 buffer to identify approximate counts of cell populations. After 30 minutes of incubation in the dark
228 at 4°C the cells were washed twice in PBS and resuspended in 100 µL buffer. Appropriate FMO
229 controls and compensation beads were used for compensation. Sample acquisition was performed
230 using Guava easyCyte 8 flow cytometer (Luminex). Data analysis was performed using GuavaSoft
231 3.3.

232 **2.19 Western blot analysis**

233 Snap-frozen mouse lung tissues were homogenized in RIPA buffer with protease inhibitor
234 cocktail and 25 µg of protein from air, VEA, MCT, and cartridge aerosol exposed mice (N=6 per
235 group for male (n=3) and female (n=3) were extracted and quantified using BCA protein assay.
236 Extracted proteins were separated on 7.5% SDS-PAGE gels, which were then transferred onto
237 nitrocellulose membranes. The membrane was probed with SP-A antibody (ab115791), ACE2
238 antibody (ab108252), Furin (ab183495), and TMPRSS2 (ab92323). B-actin (ab20272) was used as a
239 loading control for normalization.

240 **2.20 Lipidomics analysis**

241 Mouse BALF samples (200 μ L) and human plasma from one of our e-cig studies were analyzed
242 by Cayman chemicals, MI, for eicosanoids/oxylipins and short-chain-fatty-acids by LC-MS/MS. Heat
243 maps were generated depicting the changes in analytes. Analytes showing distinct differences were
244 then graphed as box-whisker plots. Untargeted lipidomic profiling was performed by normalizing
245 peak areas with internal standards. Air control samples were compared with VEA and cartridge
246 exposed samples, and only the statistically significant analytes were included in **Table 1**.

247

248 **2.21 Oil-Red-O staining**

249 Oil-Red-O staining was performed on lung OCT-cryosections and immobilized MM6 cells
250 using BioVision Cat# K580-24 according to manufacturer's instructions. In brief, the oil-red-o stock
251 was made in 20 mL 100% isopropanol. The slides were incubated in 60% isopropanol for 5 minutes,
252 followed by evenly covering with Oil-Red-O working solution. The slides were then placed on a
253 shaker and incubated for 20 minutes. After rinsing the slides with dH₂O, hematoxylin was added
254 and incubated for 1 minute. After rinsing the slides with dH₂O five times, the slides were viewed
255 under the microscope. Lipid-laden-indices were calculated in representative images of MM6 stained
256 with Oil-Red-O.

257

258 **2.22 Lipid-laden-index (LLI) scoring**

259 The method for LLI scoring of the Oil-Red-O stained monocytes was adapted from Kazachkov
260 et al. [12]. In two representative images, the total macrophages in each field were counted. Then,
261 macrophages with <50% of the cytoplasm opacified by the stain were assigned a score of "1".
262 Macrophages with >50% of the cytoplasm opacified by the stain were assigned a scored of "2". The
263 LLI was then calculated as follows: $LLI = ((\% 1 + \text{macrophages}) \times 1) + ((\% 2 + \text{macrophages}) \times 2)$.

264 **2.23 Statistical Analysis**

265 Statistical analysis of data was done by One-Way ANOVA with Tukey's multiple comparison
266 test for multiple sample groups with one variable and by Two-Way ANOVA with Tukey's multiple
267 comparison test for multiple sample groups with two variables using GraphPad Prism 8.0. Data are
268 reported by mean \pm SEM and statistical significance was reported as * $p < 0.05$, ** $p < 0.01$, and
269 *** $p < 0.001$.

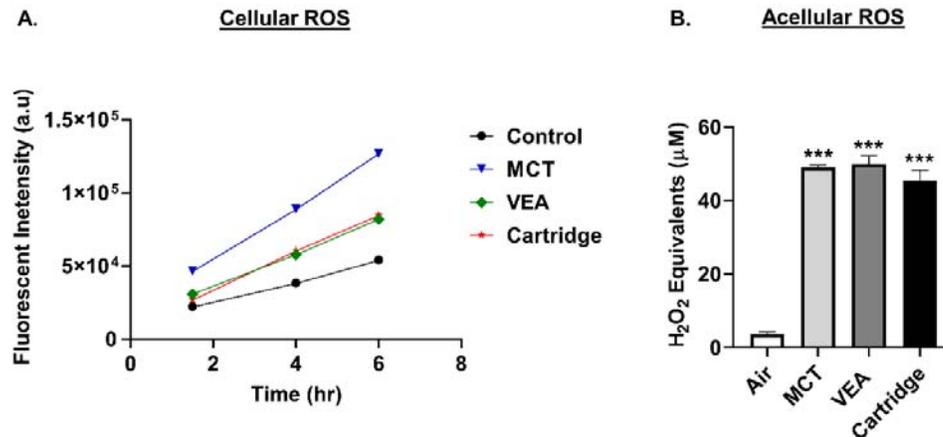
270 **3. Results**

271 **3.1 MCT, VEA, and e-cig cartridges induce cellular and acellular ROS generation and cytotoxic** 272 **responses**

273 BEAS-2B cells generated increased cellular ROS production upon treatment with MCT, VEA,
274 and cartridges compared to untreated controls. Cellular ROS levels increased with respect to time.
275 The highest cellular ROS generation was observed in MCT-treated cells, followed by VEA-treated
276 and cartridge-treated cells (N=4) (Figure 1A).

277 Acellular ROS was determined by drawing vapors from VEA, MCT, and e-cig cartridges
278 through DCFH dye. MCT, VEA, and e-cig cartridges generated significantly increased acellular ROS
279 levels (in H₂O₂ equivalents) compared to air, but did not differ between treatment groups One-way
280 ANOVA *** $p < 0.001$ vs. Air (N=2-4) (Figure 1B).

281 BEAS-2B cells exposed to VEA and e-cig cartridge aerosols caused variable cell death, although
282 non-statistically significant, compared to the air group. Among aerosols, e-cig cartridges caused the
283 greatest cytotoxicity (up to 34% cell death, n=6). Monocytes, MM6, treated with VEA or MCT did not
284 cause significantly increased cytotoxicity. However, MM6 treated with 0.25% e-cig cartridge liquid
285 caused significant cytotoxicity (up to 98%, n=9).



286

287 **Figure 1: Increased cellular and acellular generation by MCT, VEA, and e-cig cartridges.** (A)
288 Increased cellular ROS generation by cartridge liquid treatments. BEAS-2B cells were seeded at
289 15,000/well. The following day, cells were treated with 20 μM DCFH-DA in 1% FBS containing
290 media for 30 min. Cells were then washed and treated with 0.25% (v/v) MCT, 0.025% (w/v) or 50 μM
291 Vitamin E acetate, and e-cig cartridge liquids. Fluorescence (485,535nm) was read at 1.5, 4 and 6h
292 post-treatment (N=4). Control vs. MCT ***p<0.0001. Control vs. VEA *p<0.05, Control vs. Cartridge
293 p=0.2236. (B) Increased acellular generation by MCT, VEA, and e-cig cartridges. Air, 50% (w/v)
294 vitamin E acetate, MCT, and e-cig cartridges were bubbled through dichlorofluorescein diacetate
295 (DCFH-DA) dye with two 70 mL puffs. Fluorescence was measured at 485/535 nm. One-way
296 ANOVA ***p<0.001 vs. Air (N=2-4).

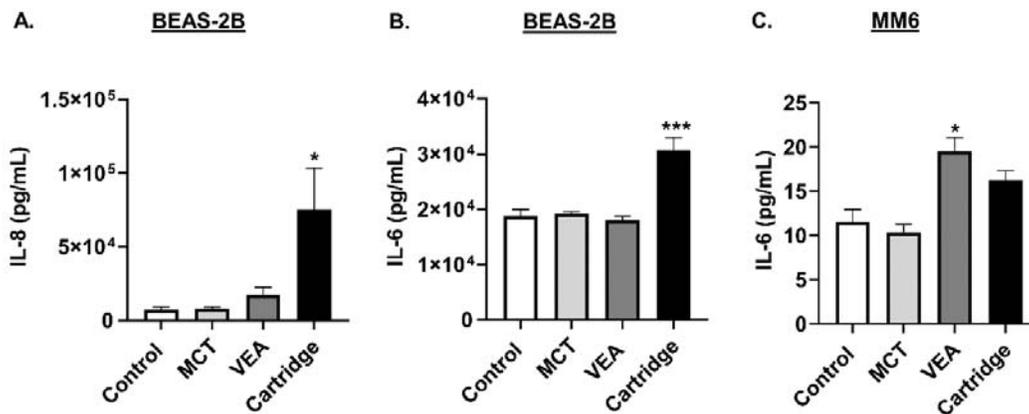
297 3.2 MCT, mineral oil, VEA, and e-cig cartridge aerosols contain volatile organic compounds

298 The highest total VOCs were released by the vape cartridges (20.03 ppm) followed by MCT
299 (10.33 ppm), then mineral oil (7.33 ppm), and VEA (9.67 ppm) compared to air (0.00 ppm).

300 3.3 Exposure to MCT, VEA, and e-cig cartridges elicited a differential inflammatory response in 301 epithelial and monocyte cells

302 Conditioned media from aerosol exposed cells were assayed for IL-8 and IL-6 to determine the
303 elicited inflammatory response by individual cells. Both MCT and VEA induced a mild increase in
304 IL-8 and IL-6 compared to their unexposed controls. Exposure to e-cig cartridge aerosols induced
305 highly significant IL-6 and IL-8 levels (One-way ANOVA, *p<0.05 and ***p<0.001 vs. control, n=6)
306 (Figure 2A,B).

307 In MM6 cells, while the treatment with MCT did not cause any changes in these cytokine levels,
308 treatment with VEA and cartridge liquid caused an elevation in IL-6 levels. VEA induced
309 significantly elevated IL-6 levels in monocytes (One-way ANOVA, *p<0.05 vs. control, n=6) (Figure
310 2C).

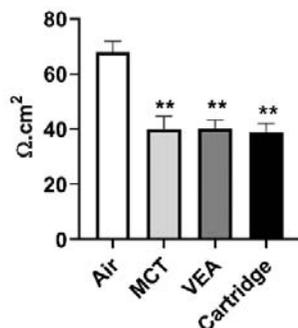


311

312 **Figure 2: Induction of differential cytotoxicity and inflammatory cytokines, IL-8 and IL-6,**
313 **responses by e-cig cartridge exposure in lung epithelial cells and monocytes.** BEAS-2B cells
314 exposed to MCT (medium-chain triglycerides) oil, vitamin E acetate (50% w/v in MCT), and e-cig
315 cartridges with 2 puffs of 70 mL in total 10 minutes. 24 hours later, cytokines (A) IL-8 and (B) IL-6
316 were measured in the conditioned media by ELISA. One-Way ANOVA * $p < 0.05$ and *** $p < 0.001$ vs.
317 control. MCT and VEA are nonsignificant vs. control (N=6/group). (C) Mono-Mac-6 cells were
318 seeded at a density of 5×10^5 cells/well in 5% FBS containing media. The following day, cells were
319 treated with 50 μ M vitamin E acetate, 0.25% MCT, and e-cig cartridges at 0.25%. 24-hours
320 post-treatment IL-6 cytokine level was measured in the conditioned media by ELISA. One-Way
321 ANOVA * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$ vs. control. $P > 0.05$ were considered nonsignificant and
322 were not denoted with asterisks (N=3-9).

323 3.4 Reduced epithelial barrier function following exposure to MCT, VEA, or e-cig cartridges

324 Trans-epithelial electrical resistance (TEER) decreased significantly in 16-HBE with the
325 treatment of all three aerosols: MCT, VEA, or e-cig cartridge. The unexposed monolayer of epithelial
326 cells' TEER was approximately 68 $\Omega \cdot \text{cm}^2$ (68.13 ± 6.39 ; n=3) while MCT, VEA, and e-cig cartridge
327 exposure resulted in a significant decrease in the TEER measurement to 40.2 $\Omega \cdot \text{cm}^2$, 40.1 $\Omega \cdot \text{cm}^2$, and
328 38.8 $\Omega \cdot \text{cm}^2$, respectively (One-way ANOVA, $p^{***} < 0.01$ vs. air, N=3) (Figure 3).

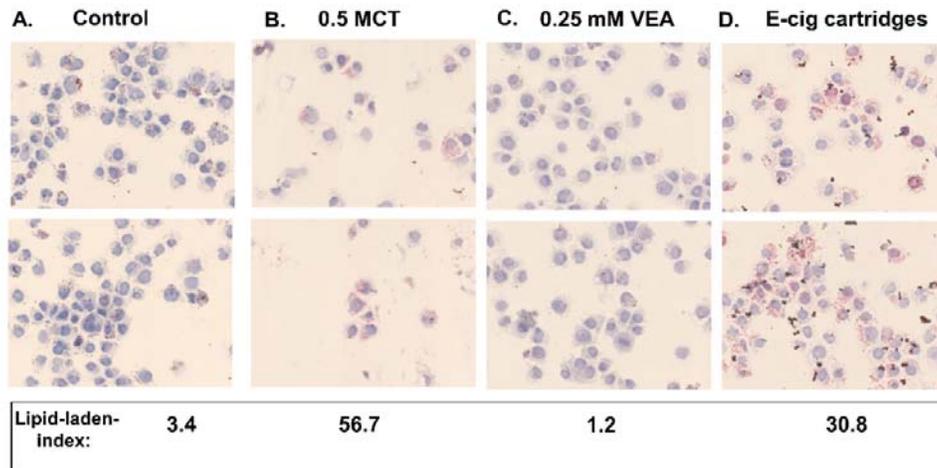


329

330 **Figure 3: Barrier dysfunction caused by e-cig cartridges in bronchial epithelial cells.** 16-HBE cells
331 were cultured on transwell inserts and exposed to 2 puffs of 70 mL of air, MCT, vitamin E acetate (50%
332 w/v), and e-cig cartridge for 10 minutes. 24-hours later, the resistance was measured by EVOM2
333 device. One-Way ANOVA ** $p < 0.01$ vs. Air (N=3).

334 **3.5 Treatment of macrophages with MCT, VEA, and e-cig cartridge liquids caused varying levels**
335 **of lipid-laden macrophage formation**

336 Treatment with MCT, VEA, or e-cig cartridges showed various levels of lipid-laden
337 macrophage formation. In representative images, treatment with MCT, VEA, and cartridges resulted
338 in lipid-laden indices of 56.7 ± 32.9 , 1.2 ± 1.6 , and 30.8 ± 3.7 , respectively, compared to 3.4 ± 4.8 for
339 untreated controls, (N=2) (Figure 4).



340

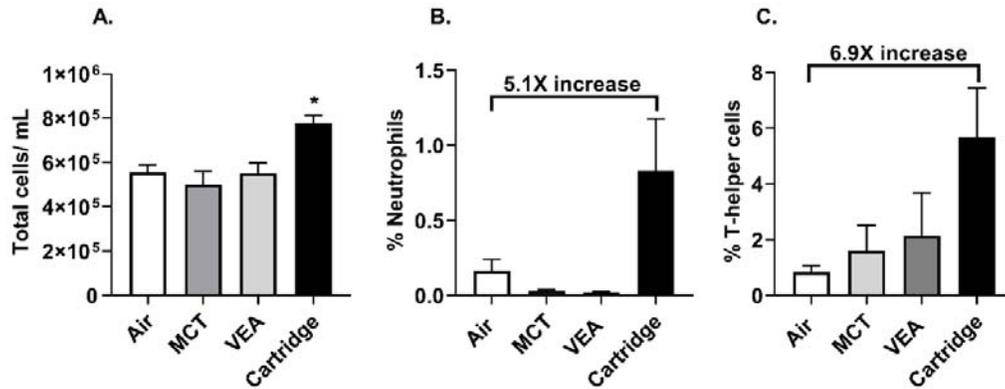
341 **Figure 4: Representative images of lipid-laden macrophages formed by MCT, VEA, and e-cig**
342 **cartridge liquid treatments.** MM6 cells were seeded in 5% complete media and treated with 0.00005%
343 (0.0003%) six unknown cartridge liquids 6h later. 24h post-treatment cells were collected and stained
344 with Oil-Red-O (N=3). The averaged lipid-laden indices of the representative images reported.

345 **3.6 Acute exposure to e-cig aerosols did not alter arterial oxygen saturation in mice**

346 Mouse arterial oxygen saturation was approximately 96%, 92%, 94%, and 95% for air, MCT,
347 VEA, and cartridge aerosol exposed mice, respectively.

348 **3.7 Exposure to e-cig cartridge aerosols induced an inflammatory response in mice**

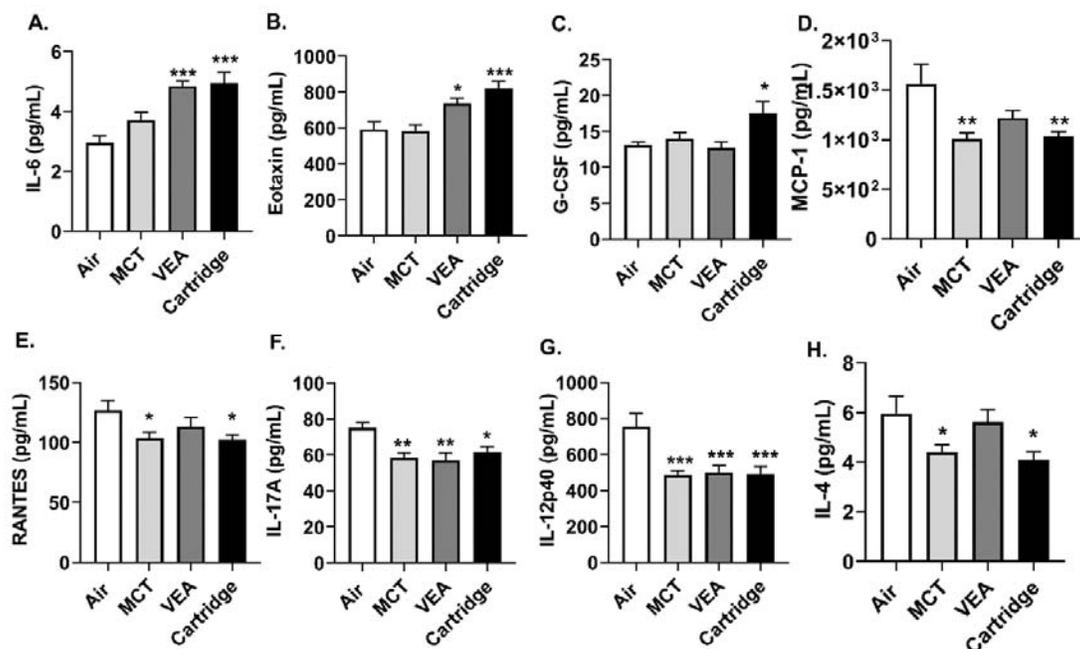
349 Acute exposure to e-cig cartridge aerosols caused increased bronchoalveolar lavage fluid (BALF)
350 total cells (one-way ANOVA * $p < 0.05$ vs. air, N=6) (Figure 5A). Neutrophils and CD4-lymphocytes in
351 the BALF increased by 5.1-fold and 6.9-fold, respectively, but these increases were not statistically
352 significant (Figure 5B,C).



353

354 **Figure 5: Exposure to aerosols from e-cig cartridges induced a differential immune cell influx.**
 355 C57BL/6 background wild type mice were exposed to MCT, vitamin E acetate 50% w/v, and six
 356 unknown cartridges with one puff a minute, 1 hour/day for three consecutive days. Mice were
 357 sacrificed immediately after the last exposure, and the immune cells in the BALF were assessed. (A)
 358 Total cells in air, MCT, VEA, and e-cig cartridge exposed BALF. One-Way ANOVA **p*<0.05 vs. Air
 359 (N=5). (B) Neutrophil count in BALF (N=5). (C) CD4+ cell count in BALF (N=5). *P*>0.05 vs. air were
 360 considered nonsignificant and were not denoted with asterisks.

361 Acute exposure to VEA and cartridges resulted in increased BALF inflammatory mediators,
 362 IL-6, and eotaxin (one-way ANOVA **p*<0.05, ****p*<0.001 vs. air, N=6) (Figure 6A,B). Granulocyte
 363 colony-stimulating factor (G-CSF) was also significantly increased in mice exposed to e-cig cartridge
 364 aerosols, but not with MCT or VEA aerosols (one-way ANOVA **p*<0.05 vs. air, N=6) (Figure 6C).
 365 Exposure to MCT, VEA, and cartridges resulted in significantly attenuated levels of MCP-1,
 366 RANTES, IL-17A, IL-12p40, and IL-4 (one-way ANOVA **p*<0.05, ***p*<0.01, and ****p*<0.001 vs. air,
 367 N=6) (Figure 6D-H).



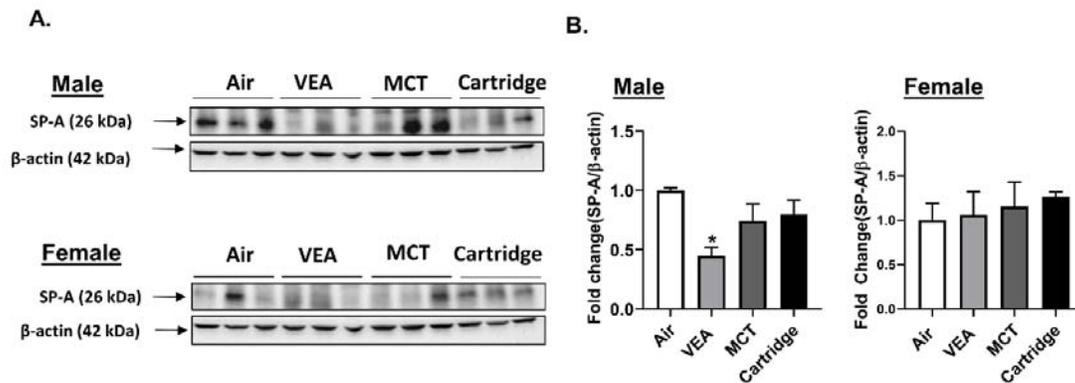
368

369

370 **Figure 6: Induction of differential cytokine response by MCT, VEA, and e-cig cartridge aerosol**
371 **exposure in mouse BALF.** Wildtype mice with C57BL/6 background were exposed to MCT, vitamin
372 E acetate 50% (w/v), and e-cig cartridges, 1 puff/min for 1 hour for three consecutive days using
373 Scireq inExpose system. Immediately after the last exposure, the mice were sacrificed and the BALF
374 was collected. Secreted inflammatory mediators were measured using BioRad 23-plex, group 1
375 Luminex kit. (A) IL-6, (B) Eotaxin, and (C) G-CSF were (D) MCP-1, (E) RANTES, (F) IL-17A, (G)
376 IL-12p40, and (H) IL-4 are reported. One-Way ANOVA * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$ vs. Air ,
377 $P > 0.05$ were considered nonsignificant and were not denoted with asterisks (N=6).

378 3.8 Surfactant-associated protein A (SP-A) reduced in VEA exposed mouse lung homogenates

379 Lung homogenates from mice exposed to air, VEA, MCT, and e-cig cartridge aerosols were
380 quantified for lung surfactant protein-A (SP-A). There was a significant reduction in SP-A in lung
381 homogenates from male mice exposed to VEA. This difference was not seen in female mice (Figure
382 7A,B).

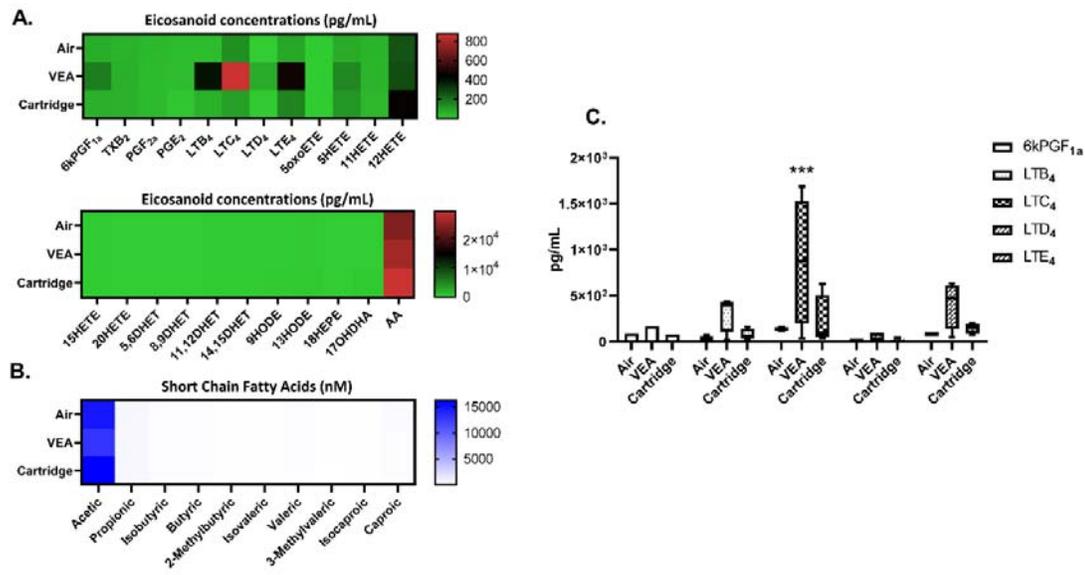


383

384 **Figure 7: Surfactant-associated protein A (SP-A) was reduced in VEA exposed mouse lung**
385 **homogenates.** (A) Surfactant-associated protein A (SP-A) protein abundance in mouse lung
386 homogenates from C57Bl/6 background male and female mice was determined by immunoblot
387 analysis. (B) The quantified results are expressed as means \pm SEM. Significance was determined by
388 1-way ANOVA with Bonferroni's correction for multiple comparisons. ** $P < 0.05$ vs. Air. $P > 0.05$
389 were considered not significant and were not denoted with asterisks (n = 3 per group for either sex).

390 3.9 Differential changes in eicosanoids/oxylipins and short-chain fatty acids in mouse BALF 391 following VEA and e-cig cartridge aerosols exposure

392 Exposure to VEA caused changes in eicosanoids, including 6kPGF1a, LTB4, LTD4, LTE4, and
393 5HETE. Exposure to e-cig cartridge aerosols increased LTB4, LTC4, LTD4, LTE4, 5HETE, and
394 12HETE. LTC4 levels were significantly elevated with VEA exposure compared to the unexposed air
395 group (one-way ANOVA *** $p < 0.001$ vs. air, N=4) (Figure 8A,C). No significant changes in
396 short-chain fatty acids were detected (Figure 8B).



397

398 **Figure 8: Eicosanoids, oxylipins, short-chain fatty acids in bronchoalveolar lavage fluid from**
 399 **VEA, and e-cig cartridge exposed mice.** Heat map generated from relative quantification by
 400 LC-NS/MS of (A)eicosanoids, oxylipins, and (B) short-chain fatty acids in BALF from mice exposed
 401 to VEA and unknown cartridges. (C) analytes, 6KPGF_{1a}, LTB₄, LTC₄, LTD₄, and LTE₄ in
 402 box-whisker plots ***p<0.001 cs. Air (N=4/ group). P>0.05 were considered nonsignificant and were
 403 not denoted with asterisks.

404 **3.10 Diradylglycerols (DG), sterols (CE), and glycerophosphocholines (PC) were significantly**
 405 **altered in VEA and cartridge aerosol expose mice.**

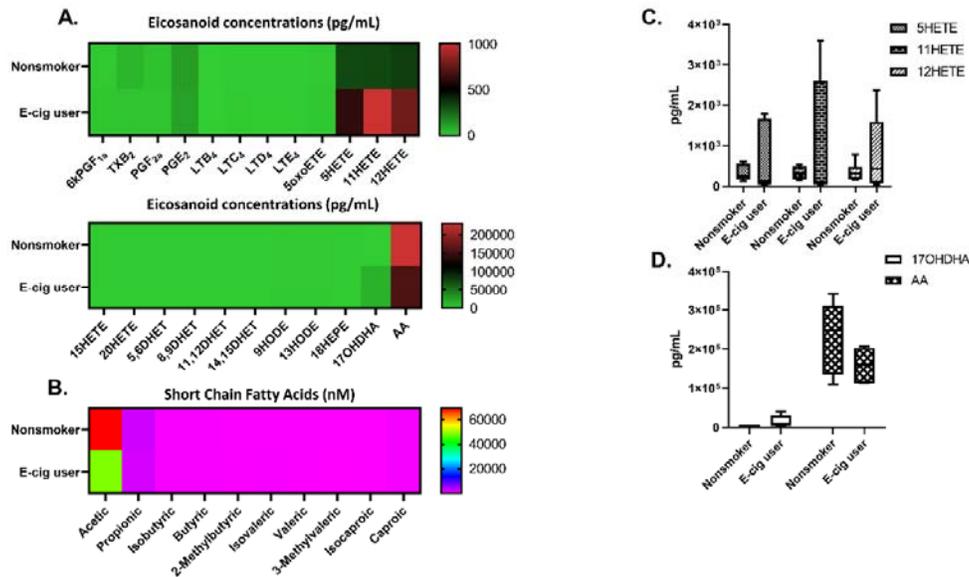
406 Lipidomic profiling on aerosol exposed mouse BALF showed changes in glycerolipids
 407 (diradylglycerols), cholesterol esters (sterols), and glycerophospholipids (glycerophosphocholines
 408 and glycerophosphoglycerols). As shown in **table 1**, DG(16:0_18:2_0:0), CE(20:4), PC(16:0/16:0), and
 409 PC(16:0_16:1), levels were significantly altered with VEA exposure in BALF. With the cartridge
 410 aerosol exposure apart from the listed above DG(16:0_16:0_0:0), PC(16:0_18:2), PC(16:0_18:1),
 411 PC(14:0_16:0), PC(16:0_22:6), PG(16:0_18:1),PG(18:2_16:0), and PG(16:0/16:0) levels were
 412 significantly altered in mouse BALF.

413 **3.11 E-cig users exhibited differential changes in eicosanoids/oxylipins and short-chain fatty**
 414 **acids in human plasma**

415 E-cig users had less TXB₂ and AA and increased levels of 5HETE, 11HETE, 12HETE, and
 416 17OHDHA levels in their plasma compared to nonsmokers (N=6) (Figure 9 A, C, D). Reduced acetic
 417 acid levels were also observed in e-cig users compared to nonsmokers (N=6) (Figure 9B).

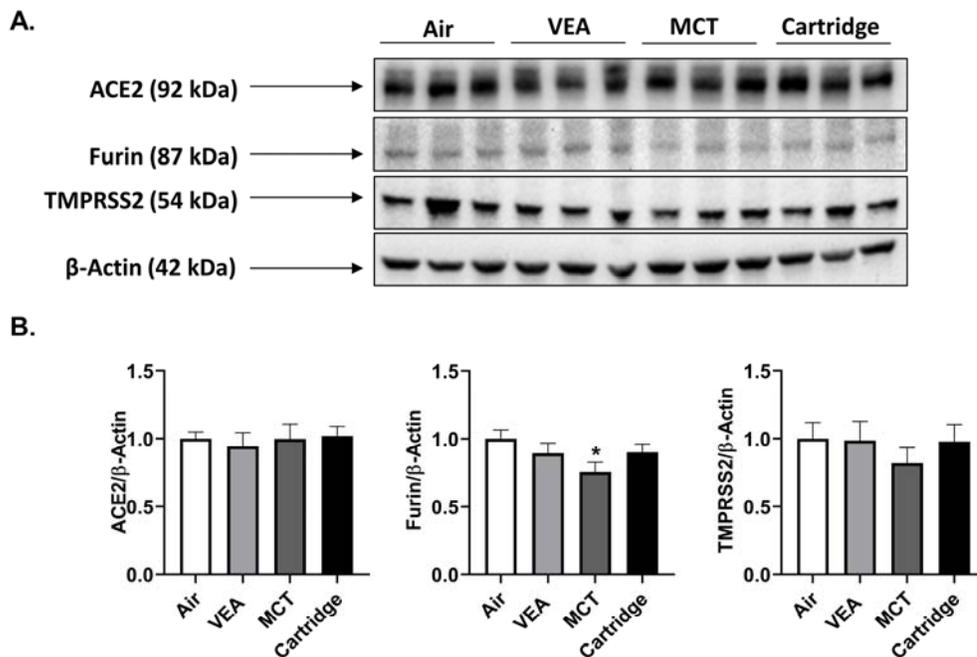
418 **3.12 SARS-COV-2 proteins ACE2, TMPRSS2, and Furin were largely unaffected by cartridge**
 419 **aerosols.**

420 Both male and female mice exposed to VEA and e-cig cartridge aerosols showed no difference in
 421 ACE2, TMPRSS2, and furin. Male mice exposed to MCT showed a significant decrease in spike
 422 protein cleaving protease, furin (Figure 10 A,B).



423

424 **Figure 9: Plasma eicosanoids, oxylipins, short-chain fatty acids in nonsmokers and e-cig users.** (A)
 425 Heat map generated from relative quantification by LC-NS/MS of eicosanoids, oxylipins, and (B)
 426 short-chain fatty acids in plasma from nonsmokers and e-cig users. (C) 5HETE, 11HETE, and
 427 12HETE levels in plasma (D) 17OHDA and AA in plasma (N=6/ group). $P > 0.05$ vs. nonsmoker
 428 were considered insignificant and were not denoted with asterisks.



429

430 **Figure 10: SARS-COV-2 spike protein cleaving enzyme, Furin, was reduced in MCT exposed in**
 431 **lung homogenates of male mice.** After the three-day acute exposure to MCT, VEA, and cartridge
 432 aerosols, the abundance of ACE2, Furin, and TMPRSS2 proteins were determined in mouse lung
 433 homogenates by immunoblotting assay. (A) Immunoblots for Ace2, Furin, TMPRSS2, and β -actin. (B)
 434 Data represented as fold-change \pm SEM * $p < 0.05$ vs. air. $P > 0.05$ were considered insignificant and were
 435 not denoted with asterisks (One-way ANOVA, N=3/group for either sex).

436
437

Analyte	Air Mean	±SEM	VEA Mean	±SEM	P-value	Significance (vs. Air)	Cartridge Mean	±SEM	P-value	Significance (vs. Air)
DG(16:0_18:2_0:0)	06.49	±0.20	05.05	±0.36	<0.001	***	04.38	±0.04	<0.001	***
DG(16:0_16:0_0:0)	00.19	±0.01	00.25	±0.04	0.5741	NS	00.40	±0.04	0.0031	**
CE(20:4)	02.77	±0.10	02.52	±0.09	0.0002	***	02.87	±0.24	0.2751	NS
PC(16:0/16:0)	29.86	±2.18	31.48	±2.41	<0.001	***	40.82	±2.64	<0.001	***
PC(16:0_16:1)	16.77	±1.42	17.59	±0.85	0.0295	*	23.46	±1.17	<0.001	***
PC(16:0_18:2)	04.31	±0.28	05.02	±0.48	0.0644	NS	06.74	±0.75	<0.001	***
PC(16:0_18:1)	04.63	±0.44	04.88	±0.17	0.6911	NS	06.64	±0.41	<0.001	***
PC(14:0_16:0)	04.22	±0.37	04.59	±0.34	0.4375	NS	05.79	±0.58	<0.001	***
PC(16:0_22:6)	01.86	±0.18	02.33	±0.32	0.2937	NS	03.18	±0.51	<0.001	***
PG(16:0_18:1)	02.70	±0.27	02.93	±0.11	0.7163	NS	03.85	±0.21	0.0014	**
PG(18:2_16:0)	02.36	±0.16	02.84	±0.22	0.2688	NS	03.93	±0.37	<0.001	***
PG(16:0/16:0)	01.73	±0.14	01.85	±0.07	0.9170	NS	02.58	±0.12	0.0237	*

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444

Table 1: Untargeted lipidomic analysis (DG: Diradylglycerols, CE: Sterols, PC: Glycerophosphocholines) in bronchoalveolar lavage fluid from air, vitamin E acetate (VEA), and cartridge aerosol exposed mice. Normalized peak area means ± SEM with P-value and significance vs. air using two-way ANOVA (*p<0.05, **0.01<p and *p<0.001 vs. Air, P>0.05 are denoted as NS, N=4/group).**

445

446 4. Discussion

447 Exposure to certain electronic nicotine delivery systems (ENDS) cartridges has recently
448 increased hospitalizations due to respiratory failure [6-8,13,14]. According to case reports since 2012,
449 e-cig users with symptoms without direct etiology have undergone various diagnoses, including
450 acute lung injury, atypical pneumonitis, and eosinophilic or lipoid pneumonia [6,13]. The presence
451 of abnormal lipid-laden macrophages in lung tissue samples from EVALI subjects has been
452 associated with lipoid pneumonia [15,16]. The patients diagnosed with lipoid-pneumonia suffered
453 from cough, difficulty in breathing, shortness of breath, chest tightness and pain, nausea, vomiting,
454 fatigue, fever, and weight loss. In one of our studies, we analyzed the chemical constituents of e-cig
455 cartridges involved in EVALI [9]. Users of these ENDS products developed varying degrees of
456 respiratory illnesses, but the mechanism of toxicity of developing EVALI is still unknown.

457 In this study, we studied the mechanisms of toxicity in developing EVALI. Constituents in e-cig
458 cartridges affect the inflammatory state of pulmonary epithelial cells, immune cells, and exposed
459 mice. MCT and mineral oil are used as the vehicle (humectant) in these cartridges. Upon heating,
460 these products emit volatile organic compounds. In cartridge aerosols, we saw nearly double the
461 amount of VOCs compared to MCT, mineral oil, or VEA aerosols. The highest total VOCs were
462 released by the vape cartridges followed by MCT oil, mineral oil, and VEA compared to air,
463 suggesting carbonyl stress by these compounds. These VOCs in e-cig cartridges can generate toxic
464 compounds, such as THC/VEA carbonyl complexes and ketene, during pyrolysis, leading to lung
465 damage [17,18]. In this study, we also observed significant acellular and cellular ROS generation by
466 cartridges and their major components. These highly reactive species vary based on vaping patterns
467 and can lead to lung pathogenesis [19]. Increased levels of IL-6 and IL-8 are clear indicators of an
468 ongoing inflammatory response in epithelial cells and monocytes. IL-8 is a potent neutrophil
469 attractant that can induce lung damage by degranulation of stored mediators and enzymes,
470 oxidative bursts, as well as the release of neutrophil extracellular traps [20,21].

471 Exposure to e-cig cartridge aerosols showed severe toxicity in monocytes, as well as
472 significantly elevated IL-6 levels, a biomarker for lung injury. This indicates that in less than 24
473 hours, the immune system can be primed towards a pro-inflammatory response [22]. In this study,
474 two puffs of aerosols significantly affected the epithelial barrier function; this is consistent with other
475 studies our lab, as well as other researchers, have published [23,24]. Toxicants emitted in these
476 aerosols damage tight junctions between the epithelial cells disrupting the epithelial barrier. This
477 alteration of the epithelial permeability drives pathogenesis by promoting inflammatory signaling
478 pathways [23,24].

479 Radiological and histological analyses of lungs with darkened patches and ground-glass
480 opacities suggest that volatile hydrocarbons such as terpenes and oils in e-cigs are possibly involved
481 in the pathogenesis of EVALI [25,26]. Various hydrocarbons and reactive aldehydes are formed
482 upon heating and thermal decomposition of e-liquids around 500 °F. All these cartridges are used at
483 around a 3.5V to 5.5 V setting using a specific device, which is similar to CBD containing cartridges.
484 These emitted chemicals may play an important role in the pathogenesis of EVALI, apart from MCT
485 and VEA. Further studies with chronic animal exposures are required for histopathological studies.

486 Formation of foamy macrophages in BALF and lung tissue has been used as a diagnostic tool
487 for vaping associated lung injuries [16,26,27]. In this study, we observed the formation of lipid-laden
488 macrophages in MM6 cells treated with MCT, VEA, and cartridges. E-cig cartridge liquids showed
489 more Oil-Red-O staining compared to VEA, suggesting that contents of these cartridges, such as
490 other oils, including MCT, can potentially cause exogenous lipoid pneumonia upon inhalation and

491 aspiration [28]. In our short 1 hr x 3 day exposure, we noticed some Oil-Red-O staining in BALF
492 macrophages; however, we did not notice any lipid-laden macrophages in lung sections (data not
493 shown), suggesting that the formation of these lipids may take longer than this exposure duration. In
494 the cytokine profile, significantly increased IL-6, eotaxin, and G-CSF were observed. Increased
495 G-CSF in BALF has been seen in patients with ARDS (acute respiratory distress syndrome), which
496 has been correlated with pulmonary neutrophilia [29-31]. This is consistent with our findings that
497 showed neutrophil influx (Figure 5A). In many cases, acute alveolitis has been associated with an
498 influx of eosinophils and neutrophils [32,33]. Similar to radiological images of lungs showing
499 ground-glass opacity, presence of lipids, and the influx of cells usually seen in cases with
500 hydrocarbon and oil inhalation have also been identified in images from vaping related lung injuries
501 [34]. The increase in eotaxin (Figure 6B) suggests eosinophilic chemotaxis in the lung tissue and
502 lavage as eotaxin plays a major role in recruiting eosinophils to the sites of inflammation [35].
503 Corroborating our data, exposure to ENDS has been shown to augment the levels of IL-6 in BALF
504 along with increased neutrophils and CD4+ cells [14].

505 In many studies, IL-6 has been shown to increase with exposure to any insult causing acute lung
506 injury to maintain the homeostasis of the inflammatory response [36-38]. The increase in G-CSF and
507 eotaxin along with the increase in CD4 cells in BALF suggest that acute exposure may be leaning
508 toward the Th2 pathway, implicating potential eosinophilic pneumonia with prolonged exposure
509 [39-41]. Excessive inflammation results in lung damage in diseases. IL-17 plays an important role in
510 leukocyte infiltration. Studies have shown reduced G-CSF secretion in IL-17R^{-/-} mice and that these
511 mice were protected against ARDS [42,43]. In this study, aerosol exposure resulted in attenuated
512 levels of MCP-1, RANTES, IL-17A, IL12p40, and IL-4 in BALF (Figure 6D-H). The occurrence of
513 eosinophilia and eosinophil alveolitis has been observed in patients with idiopathic pulmonary
514 fibrosis [44]. Consistent with observations in this study, increased CD3+ lymphocytes in BALF and
515 protection against fibrosis in IL-4 deficient mice have been observed in another study [45]. Moreover,
516 RANTES and MCP-1 are heavily involved in leukocyte influx and bronchial hyperresponsiveness
517 [46]. Similarly, the observed significant decrease in IL12p40 suggests the balancing of the
518 propagated inflammatory response as IL12p40 can be pro-inflammatory and pro-fibrotic [47]. The
519 reduction of these cytokines and chemokines implicates a negative feedback of the immune system
520 to sustain homeostasis. In a previous study, we observed that cannabidiol (CBD) containing
521 e-cigarettes possess anti-inflammatory properties by upregulating the MCP1P1 transcription factor
522 [48]. As the tested e-cig cartridges possibly contained THC and CBD, it is possible that these drugs
523 also contributed to the induced cytokine storm. Further studies are needed to understand the
524 mechanisms of this immune modulation, such as understanding the role of innate lymphoid cells
525 (ILCs) in response to exposure to e-cigarette cartridge components and toxicants. ILC2 and ILC3 are
526 pivotal to the homeostatic response to environmental toxicants with a poised immune response to
527 alleviate lung damage and maintain lung function [49].

528 In our lipidomics analysis of mouse BALF exposed to VEA and cartridge aerosols, we observed
529 increased levels of lipid mediators: leukotrienes. Leukotrienes (LTCs) are 5-lipoxygenase
530 metabolites that are vital for lung epithelial and endothelial barrier function [50]. Cysteinyl
531 leukotrienes, such as LTC₄, have been shown to play a role in allergic asthma development via
532 group 2 innate lymphoid cells (ILC2) activation and propagation [51]. In other animals such as dogs,
533 rats, and rabbits, increased LTC₄ in BALF has been seen in association with injured lungs and the
534 formation of extravascular lung water [52]. These animal studies suggest that in our murine model,
535 exposure to VEA and cartridges has promoted allergic asthma-related inflammation-causing lung
536 injury, especially in VEA exposed mice. However, it may be possible that these lower LTC₄ levels
537 seen in the cartridge exposed group may be confounded by the presence of nicotine as nicotine has
538 LTC₄ suppressive effects [53,54].

539 In e-cig users of our cohort, we observed increased systemic oxidative stress and inflammatory
540 responses [10]. These samples also showed increased hydroxyecosatetraenoic acids (HETEs) in

541 plasma. HETES are well-known biomarkers of oxidative stress, and elevated levels of HETE isomers
542 have been found in smokers [55]. In this study, we found HETE isomers 5, 11, and 12 induction in
543 e-cig users' plasma with other lipid mediators. These metabolites of arachidonic acid play an
544 important role in mediating inflammation in the lungs. HETES are involved in neutrophil
545 transcellular migration and proliferation of cells elicited inflammatory response during acute lung
546 injury [56,57]. Moreover, our untargeted lipidomics analysis showed altered glycerolipids (DG),
547 cholesterol esters (CE), and glycerophospholipids (PG and PC) in BALF. A study comparing
548 metabolomic similarities between smokers and cigarette smoke-exposed mice revealed highly
549 correlated augmented levels of glycerolipids and glycerophospholipids in mouse BALF with the
550 exposure to cigarette smoke [58]. Thus, it can be inferred that a similar modulation in lipids occurred
551 with cartridge exposures. Surfactant-associated protein A (SP-A) was reduced in lung homogenates
552 of VEA exposed male mice. Surfactant proteins are important to prevent lung atelectasis and the
553 reduction of SP-A may suggest excess accumulation of lipids in the alveolar space as we
554 demonstrated with this acute exposure. Consistent with our observations, reduced surfactant
555 proteins in BALF and lung homogenates have been seen in mice exposed to ENDS independent of
556 nicotine [14].

557 Amid the COVID-19 outbreak, smokers have shown to have more adverse outcomes upon
558 infection. In our acutely exposed lung homogenates, we looked at ACE2, TMPRSS2, and Furin
559 protein abundance and observed no association with cartridge exposures. The decrease in furin,
560 spike glycoprotein cleaving protease, in male mice with the MCT exposure needs to be further
561 investigated[59]. The exacerbated response in smokers and vapers may suggest that smoking/vaping
562 with nicotine and $\alpha 7nAChR$ with ACE2 may be involved [60].

563 Overall, based on our data, it is possible that both VEA and e-cig cartridge may have caused
564 acute respiratory distress inducing eosinophilic pneumonia. As we found in our previous study,
565 most of these cartridges contained THC derivatives and VEA [9]. At low concentrations, VEA was
566 not cytotoxic. Moreover, VEA has been employed as a carrier in therapeutic interventions [61],
567 suggesting that it may act as a carrier for THC in the blood and the brain. Upon aerosolization, VEA
568 or its formed oxidant derivatives may interact with phospholipids and surfactants of the epithelial
569 lining fluid, thus adversely affect the normal lung function [62,63]. In e-liquids, VEA is used along
570 with mineral oil and MCT oils, and there's a lack of understanding of inhalation toxicity of these
571 additives and diluents. Based on our results, MCT had lesser effects compared to VEA in vivo, but it
572 showed comparable effects to VEA in vitro; overall, cartridges containing both of these components
573 showed the greatest effects. Other than these two primary components, it may be possible that other
574 constituents in cartridges are also responsible for EVALI; those chemicals include cyclooctasiloxane,
575 cyclohexasiloxane, cyclotrisiloxane, tricaprilate, decanoic acid, benzoic acid, 2,2-dimethoxybutane,
576 and tetramethyl silicate [9].

577 In summary, this study demonstrates acute exposure to specific e-cig cartridges induce in vitro
578 cytotoxicity, barrier dysfunction, and inflammation and in vivo mouse exposure induces acute
579 inflammation with elevated pro-inflammatory markers. It was also found that SARS-COV-2 related
580 proteins had no impact associated with aerosol exposures from these tested cartridges or other
581 agents tested. Overall, this study suggests that prolonged exposure to these ENDS may cause
582 significant lung damage, which is involved in the pathogenesis of EVALI.

583

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593 **6. Author Contributions**

594 TM and IR: Conceived and designed the experiments. Wrote and edited the manuscript.

595 TM, TL, JL, and QW: Assisted in writing the manuscript, conducted experiments, performed data
596 analyses.

597 MDM: Provided scientific input and edited the manuscript.

598 **7. Competing Conflict of Interests Statement**

599 The authors declare no competing interests.

600 **8. Data availability statement**

601 We declare that we have provided all the data, but the primary data will be available upon request.

602 **9. Disclaimer:** The authors have nothing to claim or disclaim about any products used here to test
603 their toxicological and biological effects. The authors have no personal interests or gains from the
604 outcome of this study. The products tested are available commercially to consumers/users.

605

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