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Air Pollutant Emissions and Possible Health Effects Associated with Electronic Air Cleaners

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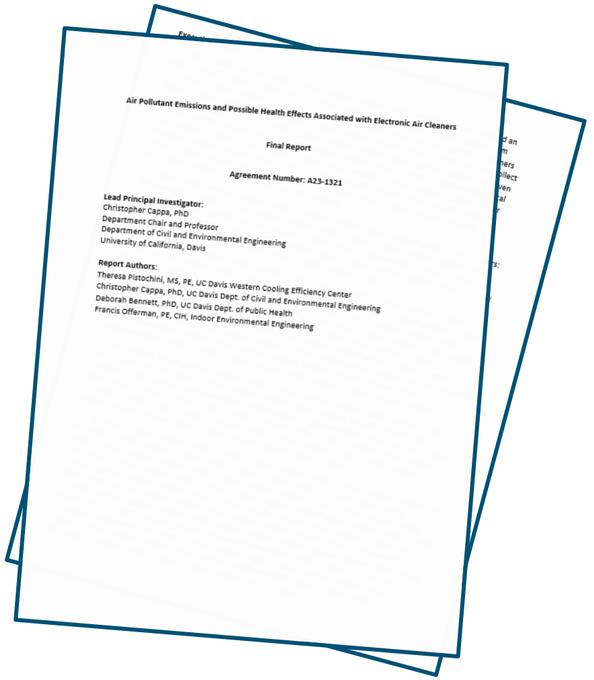

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The statements and conclusions in this Report are those of the contractor and not necessarily those of the California Air Resources Board. The mention of commercial products, their source, or their use in connection with material reported herein is not to be construed as actual or implied endorsement of such products.

Purpose

» Electronic air cleaners may emit reactive compounds or promote the formation of chemical byproducts which may have adverse health effects.

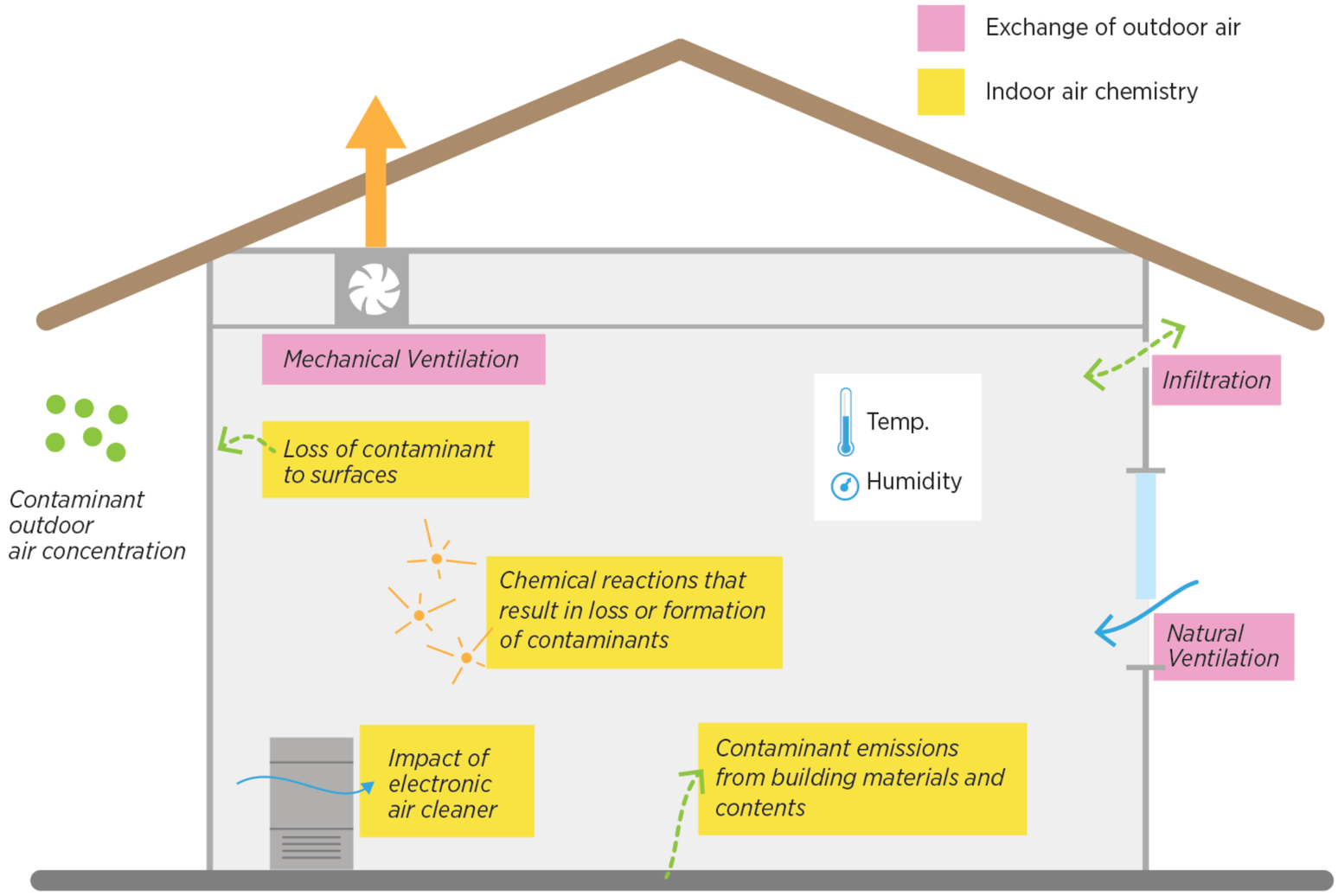
» We will summarize for electronic air cleaners:

- ☑ Types and operating principles
- ☑ Reactive compounds and byproducts emitted or formed
- ☑ Human exposure pathways and potential adverse health effects
- ☑ Test standards and regulations regarding emissions
- ☑ Gaps in understanding of the risks and recommendations for future research

» Not included:

- ⊘ Efficacy of electronic air cleaners for contaminant removal or inactivation of biological contaminants.

Varied Nature of Indoor Environment



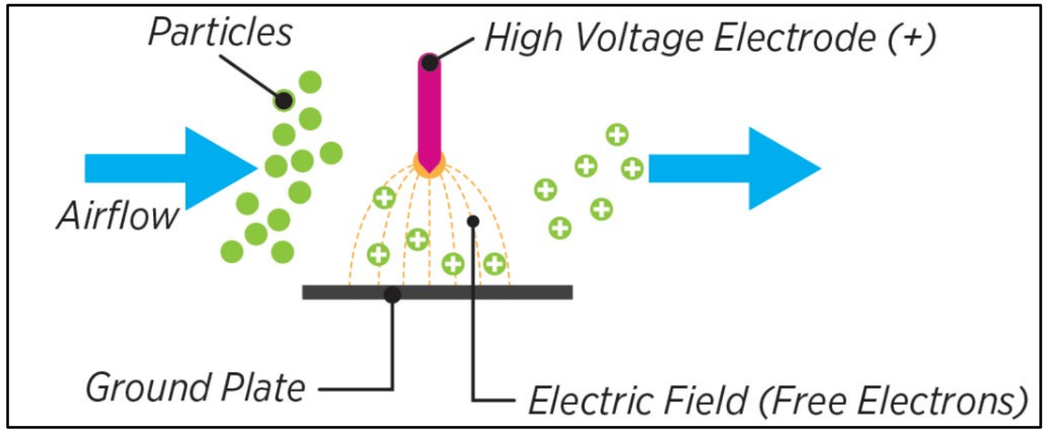
» Air cleaner emissions and byproducts impacted by the environment

Electronic Air Cleaner (EAC) Types and Operating Principles

Type: Ion Generator (IG)

Also known as: unipolar/bipolar needlepoint ionization, corona discharge, plasma generator

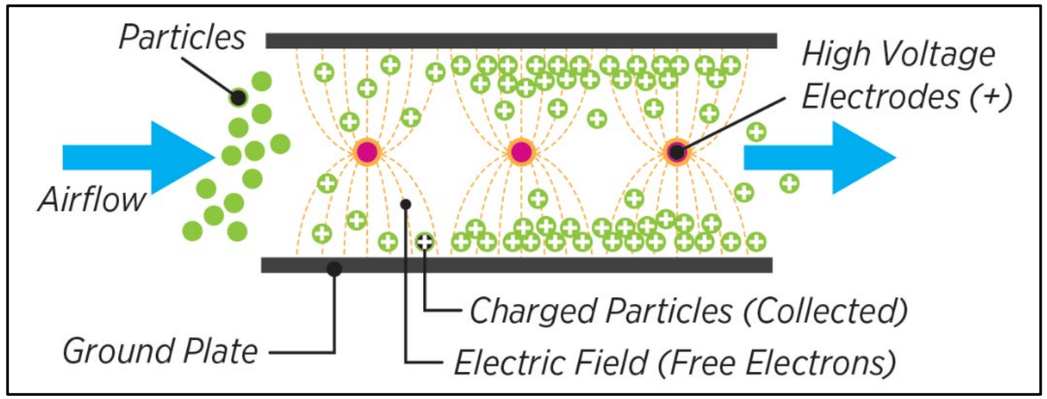
- Impart a charge on gas molecules (i.e. ions) to charge particles and increase removal by filters or deposition onto room surfaces
- High voltage to electrode creates an electric field that results in the air becoming electrically conductive
- Positive electrode – positive ions. Negative electrode – negative ions
- Ionization energy can also initiate chemical reactions in indoor air
- Electrodes ideally designed to minimize ozone production



Ion generator working principle

Type: Electrostatic Precipitator (ESP)

- Working principle similar to an ion generator
- High voltage electrodes in the form of wires
- Active removal of charged particles→ plates of opposite charge from the electrodes attract & collect charged particles
- Plates need to be cleaned periodically
- Ionization energy can also initiate chemical reactions in indoor air

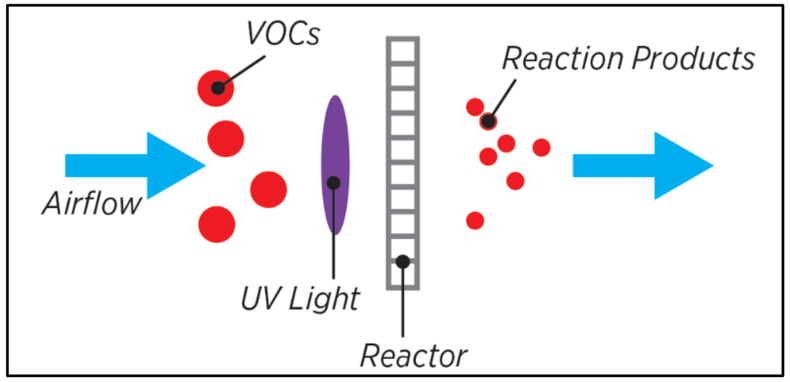


Electrostatic precipitator working principle

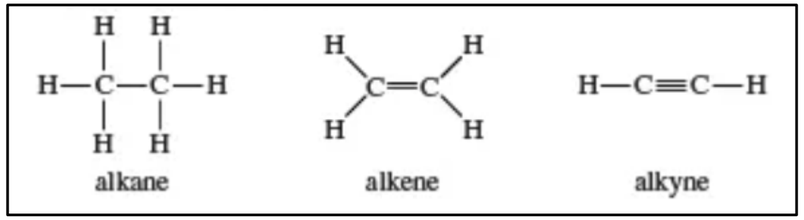
Type: Photocatalytic Oxidation (PCO)

Also known as: dry hydrogen peroxide technology

- Designed to break down volatile organic compounds (VOCs) (i.e., hydrocarbons)
- Ultraviolet (UV) radiation shines on reactor (i.e., photocatalyst) to break down water in the air and form hydroxyl radicals (•OH)
- Hydroxyl radicals react with VOCs to decompose them to carbon dioxide (CO_2) and water (H_2O) in a complete reaction
- Achieving a complete reaction is challenging and byproducts (partially decomposed VOCs) may be produced
- The UV light can initiate photolysis reactions, including ozone production



Photocatalytic oxidation working principle



Example VOCsi(e. hydrocarbons). PCO aims to break down the HC bonds to C_2O and H_2O.

Type: Ultraviolet Germicidal Irradiation

- UVC 100 – 280 nm wavelength most common
- Two types of approaches:
  - Enclosed devices that protect against human exposure
  - Devices that irradiate occupied spaces
- Safety of human exposure and disinfection performance varies by wavelength and dose (power and contact time)
- The UV light can initiate photolysis reactions, including ozone production.
- Ozone produced at wavelengths $\leqslant$ 240 nm. Maximum production at 160 nm.

Low-pressure mercury vapor

Light emitting diode (LED)

Pulse xenon arc lamp

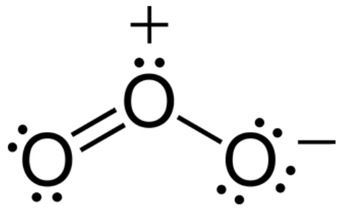
Excimer glass lamp

Other types

- Hypochlorous acid (HOCl)
  - Claim: HOCl generated from electrolysis of salt water.
  - No peer-reviewed literature found evaluating claimed working mechanism.
- Nano-confined catalytic oxidation (NCCO)
  - Contains ozone generator upstream of a catalyst to decompose VOCs.
  - Similar to PCO in working principle.
  - Achieving complete reactions is challenging.
  - Ozone emissions and byproducts (incomplete VOC breakdown) are a concern.

Potential Emissions and Health Effects

Ozone

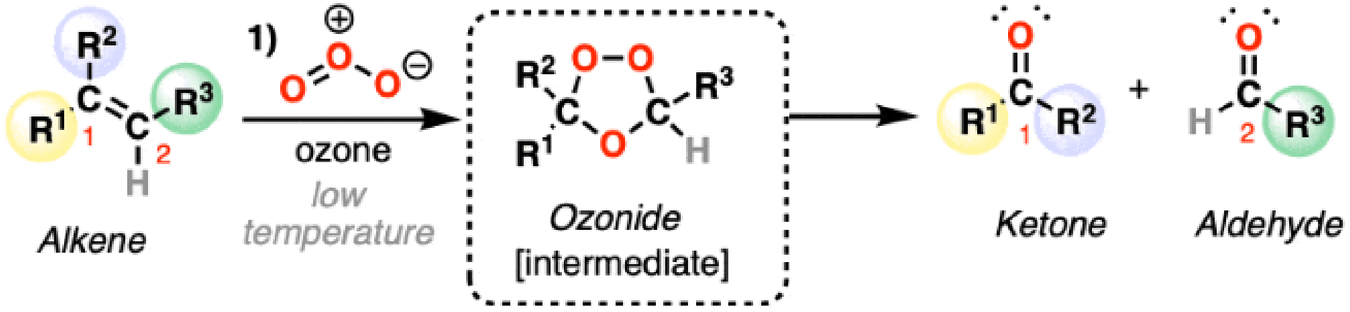


- Main source indoors is transfer from outdoor air.
- Outdoor ozone levels regulated by NAAQS (70 ppb 8-hr avg).
- Indoors generally 20 to 70% of outdoors when no indoor ozone source present.

- Health effects
  - Respiratory tract inflammation, coughing, throat irritation, aggravation of asthma, chronic bronchitis and emphysema.
  - Epidemiology studies show increase of outdoor ozone by 5 ppb associated with relative risk (RR) of 1.008 asthma-related ER visits.

Ozone Reaction Products

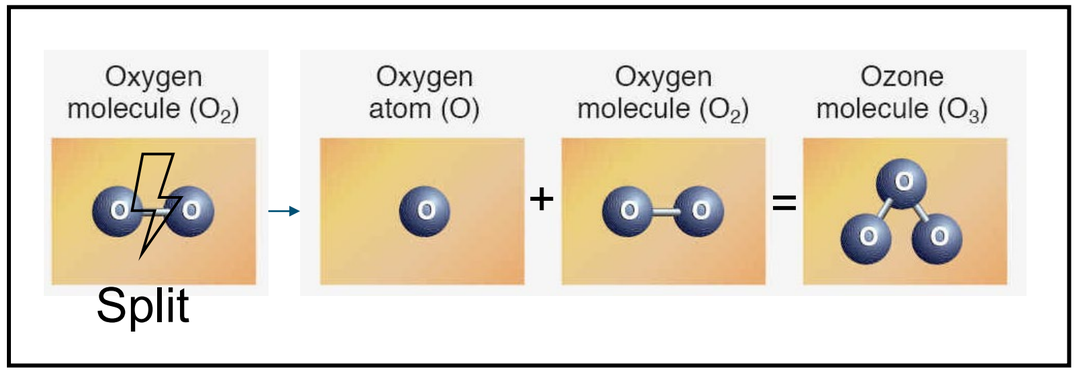
- Ozone is a reactive molecule that drives complex reactions with VOCs.
- Byproducts dependent upon what VOCs are in indoor air.
- Generally, byproducts are VOCs that contain oxygen.
- Two important byproducts are formaldehyde and acetaldehyde.
- Increased building-related symptoms with higher outdoor ozone levels (cough, dry eyes, headache, respiratory and neurological symptoms).



Example reaction of a VOC and ozone where an alkene transforms to a ketone and an aldehyde

Ozone Emissions from Air Cleaners

- Can be generated from reaction of oxygen in the room initiated by UV light, ion generator, electrostatic precipitator

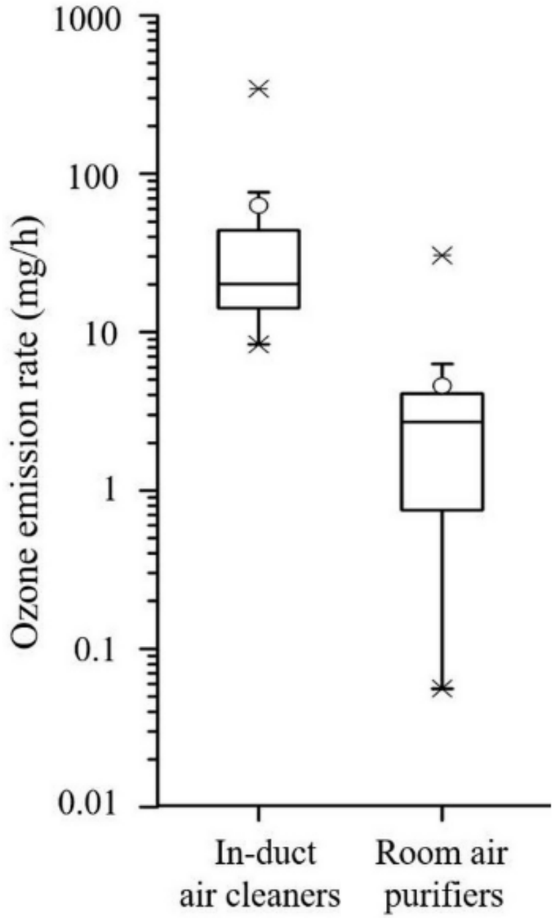


Ozone formation

- CARB requires electronic air cleaners be tested for ozone safety
- Test standard (UL 867) requires increase of less than 50 ppb in the test chamber
- Approx. equivalent to emission rate of 4 mg/ hr
- Device is tested when new

Ozone Emissions from Air Cleaners

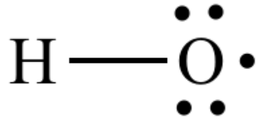
- UL 867 will prevent the highest ozone generating air cleaners from being sold.
- Passing devices can still generate ozone emissions that can meaningfully increase indoor concentrations.
- CARB regulation includes in-duct air cleaners as of October 2020.



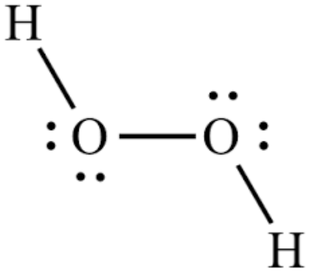
Ozone emission rates reported by Guo et al. (2019)

Other Reactive Oxygen Species

- Hydroxyl radicals and hydrogen peroxide are other highly reactive compounds derived from oxygen.
- Hydroxyl radicals have a very short lifetime and are difficult to measure. Studies indicate indoor and outdoor concentrations are similar.
- Hydrogen peroxide concentrations rarely reported in EAC studies.
  - Zeng et al. (2022) estimated 10 to 36 ppb (5 to 17 mg/hr) in testing an ion generator.
  - Well below 600 ppb observed when cleaning with hydrogen peroxide cleaning solution.
  - Well below National Institute for Occupational Safety and Health (NIOSH) 1 ppm 8-hr exposure limit.

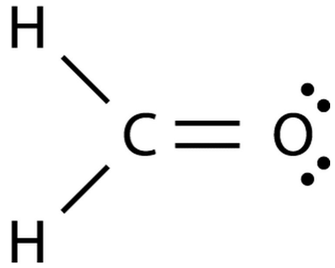


Hydroxyl radical



Hydrogen peroxide

Formaldehyde

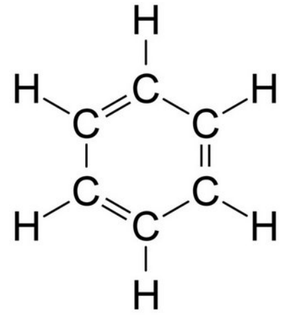


- Carcinogen and respiratory irritant
- California's Office of Environmental Health Hazard Assessment (OEHHA)
  - Safe chronic exposure limit of 7.3 ppb
  - 1 in a million cancer risk at 0.14 ppb
- EPA's Integrated Risk Information System (IRIS)
  - Reference concentration of 5.7 ppb
  - 1 in a million cancer risk at 0.13 ppb
- VOC commonly found elevated indoors
  - CA homes built 2002 to 2005 avg 35.0 ppb
  - CA homes built 2011 to 2017 avg 19.8 ppb (increased ventilation, lower emissions)
  - Still well above recommended chronic exposure levels

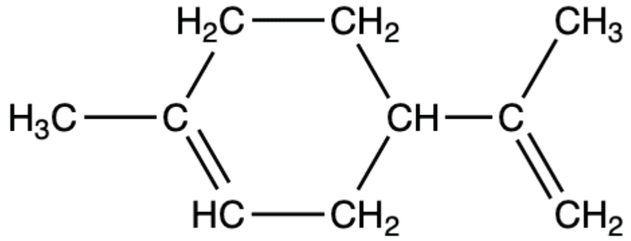
Formaldehyde

- Intermediate product formed in the breakdown of VOCs
- Will be higher in situations where more VOCs are present
- Formaldehyde production (i.e., conversion) generally observed in studies testing EAC
- Whitepaper summarizes ~10 studies
- Greater conversion (>50% on ppb basis) possible from EAC when non-aromatic VOCs are present in the room.

Aromatic: Compound with carbon ring and alternating double and single bonds.

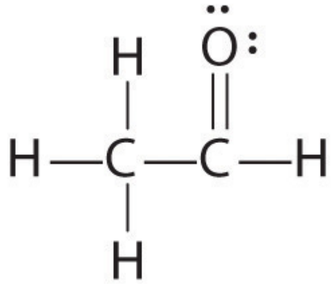


Toluene, an aromatic VOC example. Less conversion to formaldehyde.



Limonene, a non-aromatic VOC example. Greater conversion to formaldehyde.

Acetaldehyde



- Carcinogen and respiratory irritant
- Commonly observed with formaldehyde (products of VOC breakdown)
- $\frac{Acetaldehyde}{Formaldehyde}$ production from EAC was 0.15 to 1.1 across four studies
- California's Office of Environmental Health Hazard Assessment (OEHHA)
  - Safe chronic exposure limit of 77.7 ppb
  - 1 in a million cancer risk at 0.20 ppb
- EPA's Integrated Risk Information System (IRIS)
  - Reference concentration of 5 ppb
  - 1 in a million cancer risk at 0.25 ppb

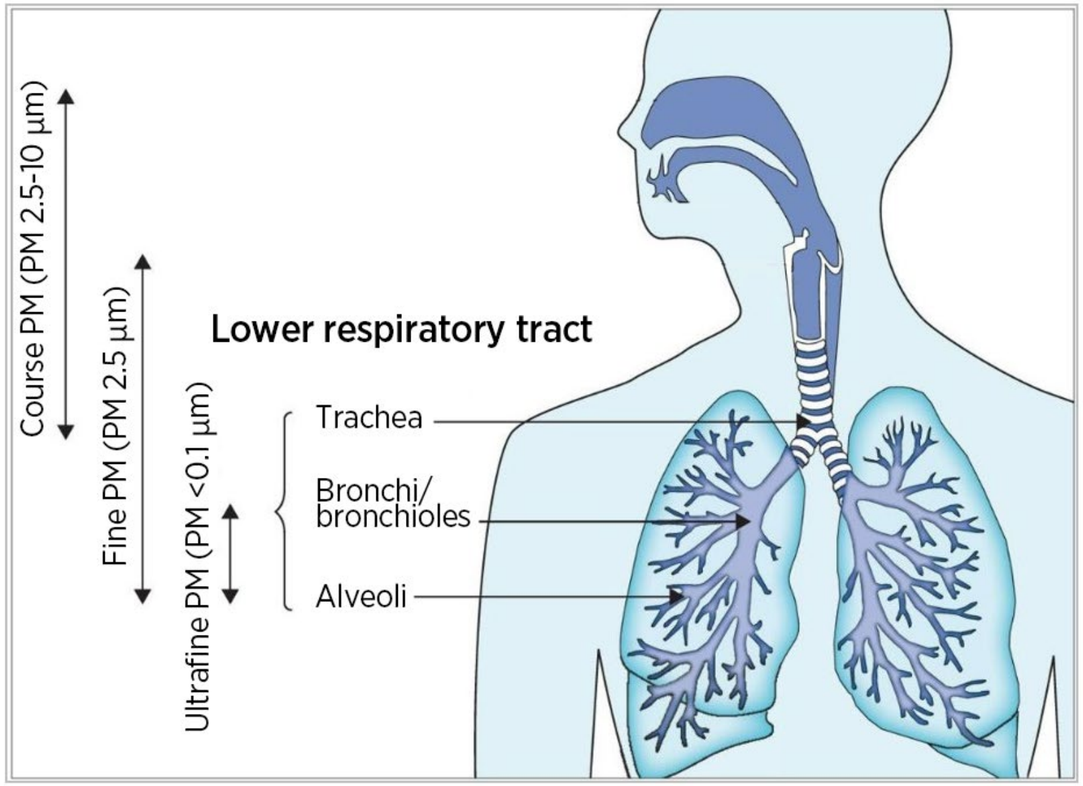
Other VOCs

- Acetone
  - Observed in ppb range
  - Eye nose and throat irritant at 250–1,000 ppm
- Acrylonitrile
  - Carcinogen observed emitted by one air cleaner in one study
  - Likely an emission from air cleaner material (heated plastic) and not EAC mechanism, a concern for many consumer products
- Propanediol, acetic acid, ethanol, and isopropanol
  - Observed in non-target analysis study by Ye et al.
  - Any adverse health effects for these compounds are at concentrations several orders of magnitude above that observed in Ye et al.

Limitation: You can only measure what your instruments are designed to detect

Ultrafine Particles (UFP)

- Aerodynamic diameter $\leq$ 0.1 µm
- Health effects: Pulmonary inflammation, heart rate variability, blood pressure cough, and worsen asthma. Linked to diabetes and low birth weight.



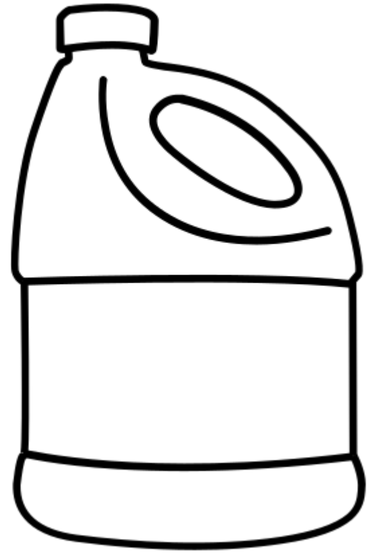
UFP penetrates respiratory system and deposits in alveoli, where it can cross into bloodstream and diffuse into organ systems.
(Figure: Guarnieri and Balmes 2014)

Ultrafine Particles (UFP)

- A byproduct of air cleaners that emit ozone
- Ozone + terpenes (VOC)→ UFP
- Terpenes are in scented products like candles, air fresheners, and cleaning products
- Yield rates of 8 to 39% terpene to UFP on a mass basis

Hypochlorous Acid (HOCl)

- No data on HOCl concentrations from air cleaners
- HOCl can reach ppb when cleaning with bleach
- HOCl can react with surfaces to form toxic chlorine gas
- Exposure to cleaning with chlorine bleach associated with respiratory and asthma symptoms, eye irritation, and sore throat
- Health risks of this type of electronic air cleaner unknown

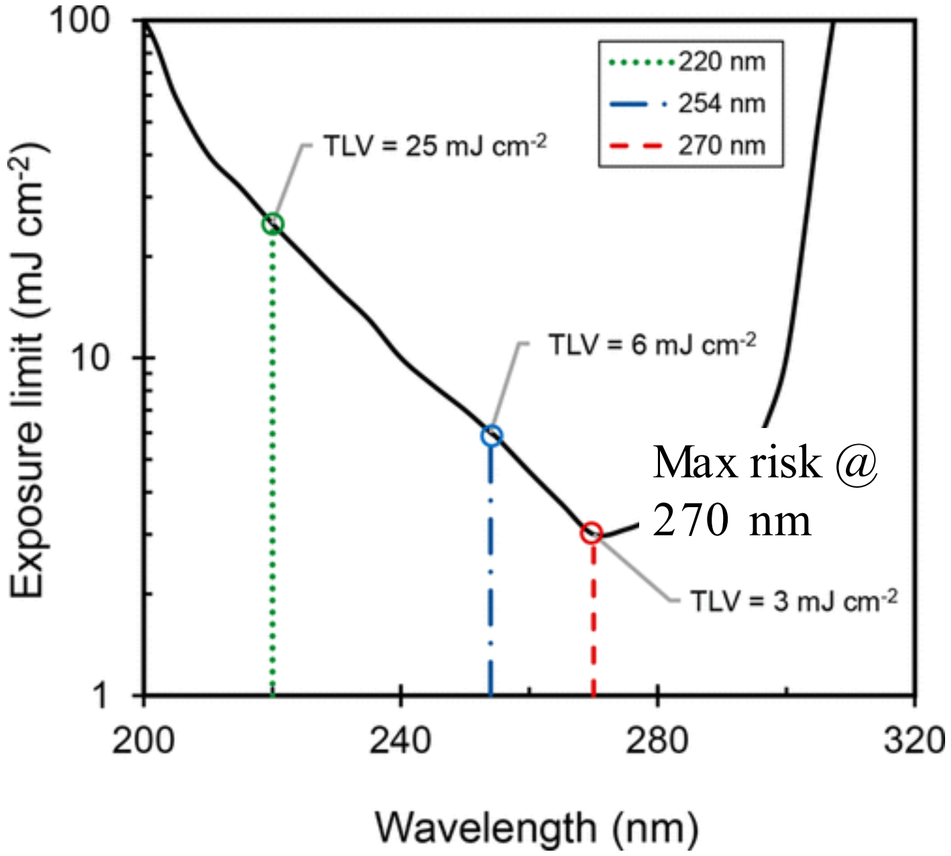


Ions and Charged Particles

- Gas or particle with an overall net electric charge
- Generally elevated with electronic air cleaners
- School children in China exhibited reduced heart rate variability (HRV) with exposure to electronic air cleaner and increased negative air ions. Lower HRV associated with increased risk of cardiovascular disease in adults.
- Deposition rates of charged particles are generally higher than neutral particles. Unknown impacts to respiratory system.

Direct UV Exposure

- Risk of cancer of skin and eyes, sunburn and skin aging, cataracts and other eye diseases.
- Guidelines developed for occupational health (does not consider children or sensitive population).
- Some disinfection performance likely achievable @ 222nm within 23 mJ/cm^2 exposure limit
- Risk is negligible for enclosed UV lamps operated as designed



Occupational 8-hour exposure limit (Raeiszadeh and Adeli, 2020)

Test Standards and Regulations

Test Standards and Regulations

- Ozone
  - UL 867 – chamber ≤ 50 ppb (~4 mg/hr)
  - UL 2998 – chamber ≤ 5 ppb (~0.4 mg/ hr)
  - AHRI 681 – 50 ppb in a test duct
- UV Safety
  - IEC 62471:2006 – measures optical radiation (total energy) and irradiation (energy per unit surface area) and compares to exposure limits. Categorizes as low-risk, moderate-risk, or high-risk.
- Chemical assessment
  - AHAM-AC-4-2002 – removal rates of five gases. No byproduct measurements.
  - ASTM-WK81750 – measurement of byproduct formed (ozone, formaldehyde, and UFP) when air cleaner challenged with chemical mix that includes ozone and VOCs.

Conclusions and Recommendations

Conclusions

- Risks versus benefits of electronic air cleaners have been inadequately studied
- No safety regulations other than ozone emission (CA only)
- Byproducts that are compounds of clear concern: ozone, formaldehyde, and ultrafine particles
- These compounds are an indicator of general byproduct production
- Major knowledge gaps exist regarding byproduct emission rates, exposure level indoors, and health effects

Knowledge Gaps

- Quantification of human exposure to compounds of clear concern
  - Test standards for measuring byproduct formation. ASTM WK81750 in process for ozone, formaldehyde, and UFP.
  - Increase in indoor air concentrations when using electronic air cleaners that emit byproducts at a quantified rate.
- Quantification of human exposure to other compounds and health effects
  - Hydrogen peroxide, hypochlorous acid, ions and ionized particles
- Health effects for direct exposure to UV light for the general population which includes infants, children, and other sensitive groups
- Quantification of air cleaner benefits (e. test standards for contaminant removal) to enable comparison of benefit versus risk.

Recommendations

- Reduce ozone emissions
  - End-users: Only use devices compliant with UL 2998 or mechanical filtration technology.
  - Regulators: Consider requiring electronic air cleaners comply with UL 2998.
- Fund research to address knowledge gaps
  - Test air cleaners to ASTM WK81750 and apply results to representative building models to estimate magnitude of increased exposure and resulting health impacts. Consider additional regulations if testing and modeling demonstrates unacceptable risk.
  - Evaluate emission rates of
    - hydrogen peroxide from PCO air cleaners
    - HOCl from HOCl generating air cleaners
  - Evaluate health effects at relevant exposure levels of:
    - hydrogen peroxide, HOC, ions and ionized particles
    - direct UV radiation considering general population (children and sensitive groups)

Thank You
Any Questions?

References

1. Klepeis, N.E., et al., *The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants.* Journal of Exposure Analysis and Environmental Epidemiology, 2001. **11**(3): p. 231-252.
2. Guo, C., Z. Gao, and J.L. Shen, *Emission rates of indoor ozone emission devices: A literature review.* Building and Environment, 2019. **158**: p. 302-318.
3. Vera, T., et al., *An overview of methodologies for the determination of volatile organic compounds in indoor air.* Applied Spectroscopy Reviews, 2022. **57**(8): p. 625-674.
4. Cooper, C.D.a.F.C.A., *Air Pollution Control: A design approach.* 4th Edition ed. 2002, Prospect Heights, IL: Waveland Press, Inc.
5. Zeng, Y., et al., *Evaluating a commercially available in-duct bipolar ionization device for pollutant removal and potential byproduct formation.* Building and Environment, 2021. **195**.
6. Kim, H.-J., et al., *Ozone Emission and Electrical Characteristics of Ionizers With Different Electrode Materials, Numbers, and Diameters.* IEEE Transactions on Industry Applications, 2017. **53**(1): p. 459-465.
7. Afshari, A., et al., *Electrostatic Precipitators as an Indoor Air Cleaner—A Literature Review.* Sustainability, 2020. **12**(21).
8. Awad, M.B. and G.S.P. Castle, *Ozone Generation in an Electrostatic Precipitator with a Heated Corona Wire.* Journal of the Air Pollution Control Association, 1975. **25**(4): p. 369-374.
9. Dorsey, J.A. and J.H. Davidson, *Ozone Production in Electrostatic Air Cleaners with Contaminated Electrodes.* Ieee Transactions on Industry Applications, 1994. **30**(2): p. 370-376.
10. Zhao, J. and X. Yang, *Photocatalytic oxidation for indoor air purification: a literature review.* Building and Environment, 2003. **38**(5): p. 645-654.
11. Mamaghani, A.H., F. Haghighat, and C.-S. Lee, *Photocatalytic oxidation technology for indoor environment air purification: The state-of-the-art.* Applied Catalysis B: Environmental, 2017. **203**: p. 247-269.
12. Tavares, R.S.N., et al., *Different biological effects of exposure to far-UVC (222 nm) and near-UVC (254 nm) irradiation.* Journal of Photochemistry and Photobiology B: Biology, 2023.
13. Schalk, S.A., Volker; Arnold, Erich; Brieden, Karl; Voronov, Alex; Witzke, Hans-Dieter, *UV-Lamps for Disinfection and Advanced Oxidation*, in *IUVA News*. 2005.
14. Mehta, I., et al., *UV Disinfection Robots: A Review.* Rob Auton Syst, 2023. **161**: p. 104332.
15. Buonanno, M., et al., *Germicidal Efficacy and Mammalian Skin Safety of 222-nm UV Light.* Radiat Res, 2017. **187**(4): p. 483-491.
16. Claus, H., *Ozone Generation by Ultraviolet Lamps.* Photochem Photobiol, 2021. **97**(3): p. 471-476.
17. Leung, A. and E. Kwok, *Evaluation of the Nano-Confined Catalytic Oxidation Technology for Air Purification and Odor Reduction.* Advanced Materials Research, 2012. **550-553**: p. 607-615.
18. Wu, R., et al., *Numerical study on catalytic combustion of methane with ozone using Pd-exchanged zeolite X.* Science China-Chemistry, 2015. **58**(5): p. 899-904.
19. US Environmental Protection Agency. *What is a HEPA filter?* 2023; Available from: https://www.epa.gov/indoor-air-quality-iaq/what-hepa-filter.
20. Bhave, P.P. and D. Yeleswarapu, *Removal of Indoor Air Pollutants Using Activated Carbon-A Review.* Global Challenges in Energy and Environment (Icee 2018), 2020: p. 65-75.
21. US Environmental Protection Agency. *NAAQS Table*. 2023 [cited 2023 May 11]; Available from: https://www.epa.gov/criteria-air-pollutants/naaqs-table.
22. Organization, W.H., *WHO global air quality guidelines*. 2021.
23. United States Environmental Protection Agency, *Health Risk and Exposure Assessment for Ozone*, O.o.A.a. Radiation, Editor. 2014.
24. Zheng, X.Y., et al., *Short-term exposure to ozone, nitrogen dioxide, and sulphur dioxide and emergency department visits and hospital admissions due to asthma: A systematic review and meta-analysis.* Environment International, 2021. **150**.
25. Weschler, C.J., *Ozone in indoor environments: Concentration and chemistry.* Indoor Air-International Journal of Indoor Air Quality and Climate, 2000. **10**(4): p. 269-288.
26. Jenkin, M.E., S.M. Saunders, and M.J. Pilling, *The tropospheric degradation of volatile organic compounds: a protocol for mechanism development.* Atmospheric Environment, 1997. **31**(1): p. 81-104.
27. Buchanan, I.S.H., et al., *Air filter materials, outdoor ozone and building-related symptoms in the BASE study.* Indoor Air, 2008. **18**(2): p. 144-155.
28. Rohr, A.C., *The health significance of gas- and particle-phase terpene oxidation products: A review.* Environment International, 2013. **60**: p. 145-162.
29. Wolkoff, P., *Indoor air chemistry: Terpene reaction products and airway effects.* International Journal of Hygiene and Environmental Health, 2020. **225**.
30. Kipen, H.M., et al., *Acute decreases in proteasome pathway activity after inhalation of fresh diesel exhaust or secondary organic aerosol.* Environ Health Perspect, 2011. **119**(5): p. 658-63.
31. Wilkins, C.K., et al., *Upper airway irritation of terpene/ozone oxidation products (TOPS). Dependence on reaction time, relative humidity and initial ozone concentration.* Toxicology Letters, 2003. **143**(2): p. 109-114.
32. Laboratories, U., *Standard for Safety, Electrostatic Air Cleaners*. 2018, Underwriters Laboratories.
33. Zhe, P., et al., *Significant Production of Ozone from Germicidal UV Lights at 222 nm.* medRxiv, 2023: p. 2023.05.13.23289946.
34. Weschler, C.J. and H.C. Shields, *Measurements of the hydroxyl radical in a manipulated but realistic indoor environment.* Environmental Science & Technology, 1997. **31**(12): p. 3719-3722.
35. Carslaw, N., *A new detailed chemical model for indoor air pollution.* Atmospheric Environment, 2007. **41**(6): p. 1164-1179.
36. Zeng Y, L.A., Gall ET, Heidarinejad M, Stephens B., *Experimental Evaluations of the Impact of an Additive Oxidizing Electronic Air Cleaner on Particles and Gases.* Pollutants, 2022. **2**(2): p. 36.
37. Zhou, S., et al., *Hydrogen Peroxide Emission and Fate Indoors during Non-bleach Cleaning: A Chamber and Modeling Study.* Environ Sci Technol, 2020. **54**(24): p. 15643-15651.
38. National Institute for Occupational Safety and Health (NIOSH). *Hydrogen peroxide*. 2019 [cited 2023 August 1].
39. Salthammer, T., S. Mentese, and R. Marutzky, *Formaldehyde in the Indoor Environment.* Chemical Reviews, 2010. **110**(4): p. 2536-2572.
40. California Code of Regulations, *Airborne Toxic Control Measure to Reduce Formaldehyde Emissions from Composite Wood Products*, in *17*.
41. Rovira, J., et al., *Human health risks of formaldehyde indoor levels: An issue of concern.* Journal of Environmental Science and Health, Part A, 2016. **51**(4): p. 357-363.
42. Singer, B.C., et al., *Indoor air quality in California homes with code-required mechanical ventilation.* Indoor Air, 2020. **30**(5): p. 885-899.
43. Assessment, C.O.o.E.H.H. *Formaldehyde*. 2008 [cited 2023 May 5]; Available from: https://oehha.ca.gov/chemicals/formaldehyde.
44. Agency, U.E.P., *Toxicological Review of Formaldehyde Inhalation*, I.R.I. System, Editor. 2022, US Environmental Protection Agency: Washington DC.

References

45. Bauwens, M., et al., *Nine years of global hydrocarbon emissions based on source inversion of OMI formaldehyde observations.* Atmos. Chem. Phys., 2016. **16**(15): p. 10133-10158.
46. Zhu, L., et al., *Formaldehyde (HCHO) As a Hazardous Air Pollutant: Mapping Surface Air Concentrations from Satellite and Inferring Cancer Risks in the United States.* Environmental Science & Technology, 2017. **51**(10): p. 5650-5657.
47. Waring, M.S., J.A. Siegel, and R.L. Corsi, *Ultrafine particle removal and generation by portable air cleaners.* Atmospheric Environment, 2008. **42**(20): p. 5003-5014.
48. Waring, M.S. and J.A. Siegel, *The effect of an ion generator on indoor air quality in a residential room.* Indoor Air, 2011. **21**(4): p. 267-76.
49. Crawford, T., P. Fritz, and T. Wainman, *Changes in IAQ Caused by Corona Discharge Air Cleaner.* ASHRAE Journal, 2018: p. 4.
50. Gunschera, J., et al., *Portable photocatalytic air cleaners: efficiencies and by-product generation.* Environmental Science and Pollution Research, 2016. **23**(8): p. 7482-7493.
51. Hoang, T., et al., *VOC exposures in California early childhood education environments.* Indoor Air, 2017. **27**(3): p. 609-621.
52. Ye, Q., et al., *Real-Time Laboratory Measurements of VOC Emissions, Removal Rates, and Byproduct Formation from Consumer-Grade Oxidation-Based Air Cleaners.* Environmental Science & Technology Letters, 2021. **8**(12): p. 1020-1025.
53. Sleiman, M., et al., *Photocatalytic oxidation of toluene at indoor air levels (ppbv): Towards a better assessment of conversion, reaction intermediates and mineralization.* Applied Catalysis B: Environmental, 2009. **86**(3): p. 159-165.
54. Mo, J., Y. Zhang, and Q. Xu, *Effect of water vapor on the by-products and decomposition rate of ppb-level toluene by photocatalytic oxidation.* Applied Catalysis B: Environmental, 2013. **132-133**: p. 212-218.
55. Farhanian, D. and F. Haghighat, *Photocatalytic oxidation air cleaner: Identification and quantification of by-products.* Building and Environment, 2014. **72**: p. 34-43.
56. Hodgson, A.I., et al., *Performance of ultraviolet photocatalytic oxidation for indoor air cleaning applications.* Indoor Air, 2007. **17**(4): p. 305-316.
57. Aumont, B., S. Szopa, and S. Madronich, *Modelling the evolution of organic carbon during its gas-phase tropospheric oxidation: development of an explicit model based on a self generating approach.* Atmospheric Chemistry and Physics, 2005. **5**: p. 2497-2517.
58. Barkjohn, K.K., B. Gantt, and A.L. Clements, *Development and application of a United States-wide correction for PM2.5 data collected with the PurpleAir sensor.* Atmospheric Measurement Techniques, 2021. **14**(6): p. 4617-4637.
59. Mo, J., et al., *Photocatalytic purification of volatile organic compounds in indoor air: A literature review.* Atmospheric Environment, 2009. **43**(14): p. 2229-2246.
60. Graeffe, F., et al., *Unwanted Indoor Air Quality Effects from Using Ultraviolet C Lamps for Disinfection.* Environmental Science & Technology Letters, 2023. **10**(2): p. 172-178.
61. Assessment, C.O.o.E.H.H. *Acetaldehyde*. 2013 [cited 2023 May 5]; Available from: https://oehha.ca.gov/proposition-65/chemicals/acetaldehyde.
62. Agency, U.E.P., *Acetaldehyde; CASRN 75-07-0*, I.R.I. System, Editor. 1991, US Environmental Protection Agency: Washington DC.
63. Dalton, P., et al., *Perceived odor, irritation, and health symptoms following short-term exposure to acetone.* American Journal of Industrial Medicine, 1997. **31**(5): p. 558-569.
64. Mitran, E., et al., *Neurotoxicity associated with occupational exposure to acetone, methyl ethyl ketone, and cyclohexanone.* Environmental Research, 1997. **73**(1-2): p. 181-188.
65. Agency, U.E.P., *Acrylonitrile; CASRN 107-13-1*, I.R.I. System, Editor. 1991, US Environmental Protection Agency: Washington DC.
66. Scott, R.S., et al., *Inhalation toxicity of 1,3-propanediol in the rat.* Inhalation Toxicology, 2005. **17**(9): p. 487-493.
67. Ernstgard, L., et al., *Acute effects of exposure to vapours of acetic acid in humans.* Toxicology Letters, 2006. **165**(1): p. 22-30.
68. Coon, R.A.J., R.A, Jenkins, L.J, Siegel, J., *Animal inhalation studies on ammonia, ethylene glycol, formaldehyde, dimethylamine, and ethanol.* Toxicology and Applied Pharmacology, 1970. **16**(3): p. 10.
69. Burleighflayer, H.D., et al., *Isopropanol 13-Week Vapor Inhalation Study in Rats and Mice with Neurotoxicity Evaluation in Rats.* Fundamental and Applied Toxicology, 1994. **23**(3): p. 421-428.
70. Schraufnagel, D.E., *The health effects of ultrafine particles.* Experimental and Molecular Medicine, 2020. **52**(3): p. 311-317.
71. Ohlwein, S., et al., *Health effects of ultrafine particles: a systematic literature review update of epidemiological evidence.* International Journal of Public Health, 2019. **64**(4): p. 547-559.
72. Corsi, R.L., *Assessment of Maximum Ozone Emissions in Residential, Office and School Buildings*. 2006, University of Texas at Austin.
73. Hubbard, H.F., et al., *Effects of an ozone-generating air purifier on indoor secondary particles in three residential dwellings.* Indoor Air, 2005. **15**(6): p. 432-44.
74. Collins, D.B. and D.K. Farmer, *Unintended Consequences of Air Cleaning Chemistry.* Environ Sci Technol, 2021. **55**(18): p. 12172-12179.
75. Mattila, J.M., et al., *Multiphase Chemistry Controls Inorganic Chlorinated and Nitrogenated Compounds in Indoor Air during Bleach Cleaning.* Environmental Science & Technology, 2020. **54**(3): p. 1730-1739.
76. Nazaroff, W.W. and C.J. Weschler, *Cleaning products and air fresheners: exposure to primary and secondary air pollutants.* Atmospheric Environment, 2004. **38**(18): p. 2841-2865.
77. Quirce, S. and P. Barranco, *Cleaning Agents and Asthma.* Journal of Investigational Allergology and Clinical Immunology, 2010. **20**(7): p. 542-550.
78. De Troeyer, K., et al., *Identifying cleaning products associated with short-term work-related respiratory symptoms: A workforce-based study in domestic cleaners.* Environment International, 2022. **162**.
79. Weisel, C.P., et al., *Childhood Asthma and Environmental Exposures at Swimming Pools: State of the Science and Research Recommendations.* Environmental Health Perspectives, 2009. **117**(4): p. 500-507.
80. Alexander, D.D., et al., *Air ions and respiratory function outcomes: a comprehensive review.* Journal of Negative Results in Biomedicine, 2013. **12**.
81. Dong, W., et al., *Different cardiorespiratory effects of indoor air pollution intervention with ionization air purifier: Findings from a randomized, double-blind crossover study among school children in Beijing.* Environ Pollut, 2019. **254**(Pt B): p. 113054.
82. Kubota, Y., et al., *Heart rate variability and lifetime risk of cardiovascular disease: the Atherosclerosis Risk in Communities Study.* Annals of Epidemiology, 2017. **27**(10): p. 619-625.
83. Cohen, B.S., et al., *Deposition of charged particles on lung airways.* Health Physics, 1998. **74**(5): p. 554-560.
84. Majid, H., et al., *Implementation of Charged Particles Deposition in Stochastic Lung Model and Calculation of Enhanced Deposition.* Aerosol Science and Technology, 2012. **46**(5): p. 547-554.
85. Stabile, L., et al., *Charged particles and cluster ions produced during cooking activities.* Sci Total Environ, 2014. **497-498**: p. 516-526.
86. Jayaratne, E.R., X. Ling, and L. Morawska, *Comparison of charged nanoparticle concentrations near busy roads and overhead high-voltage power lines.* Sci Total Environ, 2015. **526**: p. 14-8.

References

87. Raeiszadeh, M. and B. Adeli, *A Critical Review on Ultraviolet Disinfection Systems against COVID-19 Outbreak: Applicability, Validation, and Safety Considerations*. Acs Photonics, 2020. **7**(11): p. 2941-2951.
88. Navy and Marine Corps Public Health Center, *Industrial Hygiene Field Operations Manual: Technical Manual NMCPHC-TM6290.91-2 22 N*. 2019.
89. McKinlay, A.F., et al., *Guidelines on limits of exposure to ultraviolet radiation of wavelengths between 180 nm and 400 nm (incoherent optical radiation)*. Health Physics, 2004. **87**(2): p. 171-186.
90. Sliney, D.H. and B.E. Stuck, *A Need to Revise Human Exposure Limits for Ultraviolet UV-C Radiation(dagger)*. Photochem Photobiol, 2021. **97**(3): p. 485-492.
91. Buonanno, M., et al., *Far-UVC light (222 nm) efficiently and safely inactivates airborne human coronaviruses*. Sci Rep, 2020. **10**(1): p. 10285.
92. Peng, Z., S.L. Miller, and J.L. Jimenez, *Model Evaluation of Secondary Chemistry due to Disinfection of Indoor Air with Germicidal Ultraviolet Lamps*. Environmental Science & Technology Letters, 2023. **10**(1): p. 6-13.
93. California Code of Regulations, *Regulation for Limiting Ozone Emissions from Air Cleaning Devices*, in *Title 17, Division 3, Chapter 1, Subchapter 8.7, Article 1*.
94. Underwriters Laboratories, *Standard 867: Electrostatic Air Cleaners*. Northbrook, IL.
95. Underwriters Laboratory, *Standard 2998: Environmental Claim Validation Procedure (ECVP) for Zero Ozone Emissions from Air Cleaners*. Northbrook, IL.
96. Air Conditioning, H., and Refrigeration Institute,, *Standard 681: Performance Rating of Residential Air Filter Equipment*. 2017: Arlington, VA.
97. Link, M., Poppendieck, D., *Ozone emissions from 222 nm GUV lamps and potential impacts on Indoor Air Quality*. 2023: Presentation to The Federal Interagency Committee on Indoor Air Quality.
98. Association of Home Appliance Manufacturers, *AHAM AC-4-2022 Method of Assessing the Chemical Reduction Rate of Chemical Gases by a Room Air Cleaner*. 2022: Washington, DC.

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