

Energy-Related Indoor  
Environmental Quality Research:  
Small and Medium  
Commercial Buildings, Field Study

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# Small and medium-sized commercial buildings

- Constructed after 1978
- Floor area between 1,000 and 50,000 ft<sup>2</sup>
- Fewer than four stories
- Roof-top ventilation and air conditioning units

# Objectives

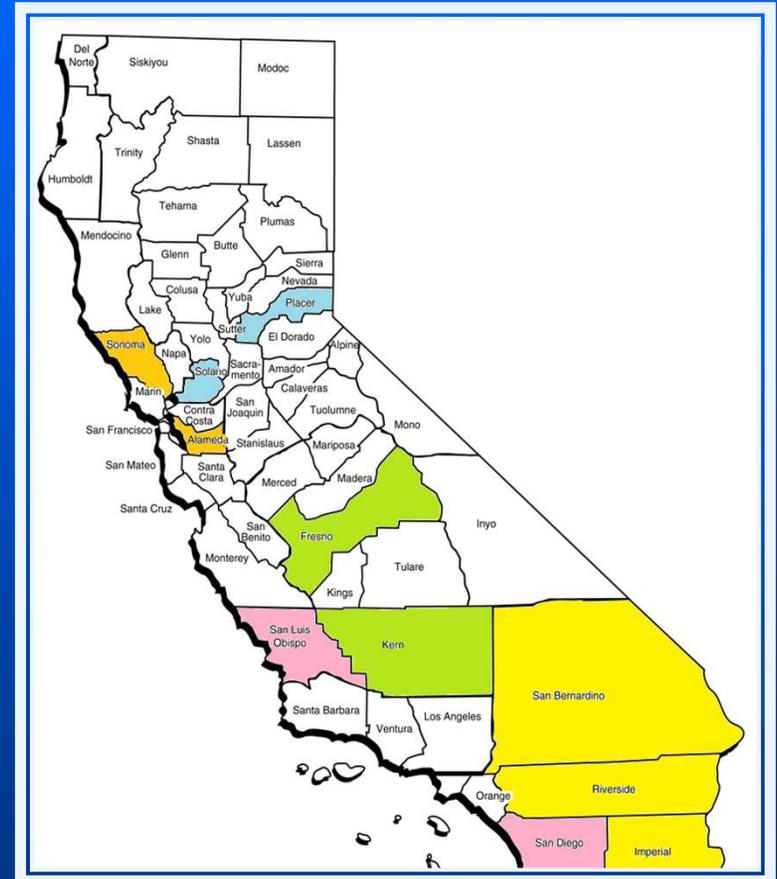
1. Obtain data on maintenance of HVAC and air filtration systems
2. Obtain field data on the design and performance parameters of HVAC and air filtration systems
3. Obtain data on indoor pollutant levels for particulate matter and VOCs
4. Estimate penetration rates for particulate matter
5. Analyze relationships between and among parameters
6. Recommendations

# Selecting Buildings

- Phase 1 (LBNL & Berkeley Survey Research) 476 Buildings
- Phase 2 - Field evaluation of 37 buildings (with 3 repeats to total 40)
- 28 buildings participated in Phase 1
- Difficult building types were convenience
  - dentists, hair salons, grocery, restaurant, gym
- Additional buildings through a sequential process using a publically available database
  - retail in central and southern inland regions

# Building Distribution

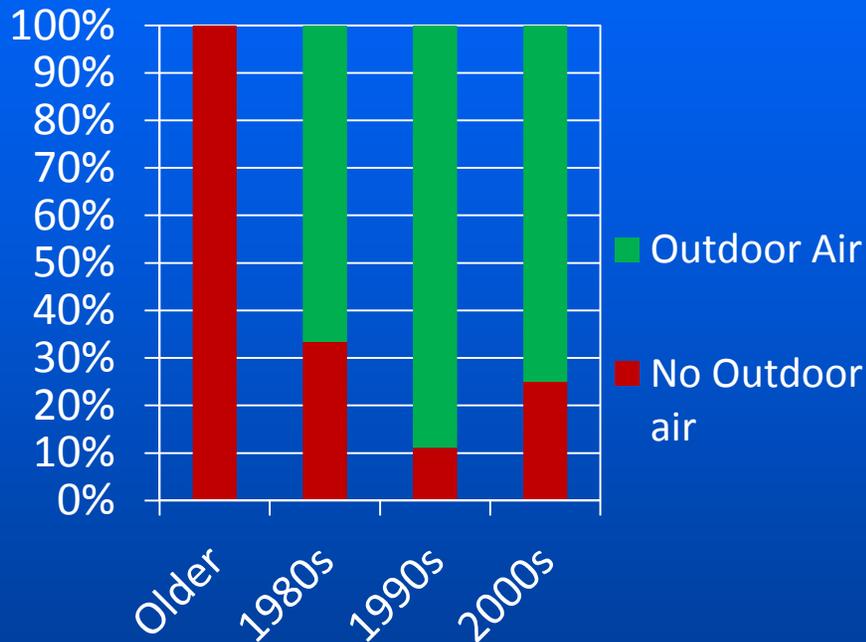
Building type	No.	Range in sq. ft.
<b>Retail</b>	7	1,000-24,037
<b>Restaurant</b>	5	900-5,652
<b>Office</b>	8	1,500-28,620
<b>Gas Station</b>	2	2,000-3,600
<b>Hair Salon</b>	2	1,000-2,321
<b>Health Care</b>	2	15,000-39,000
<b>Grocery</b>	2	20,000-50,000
<b>Dentist</b>	2	700-1,500
<b>Gym</b>	2	1,000-33,037
<b>Other</b>	5	1,700-12,000



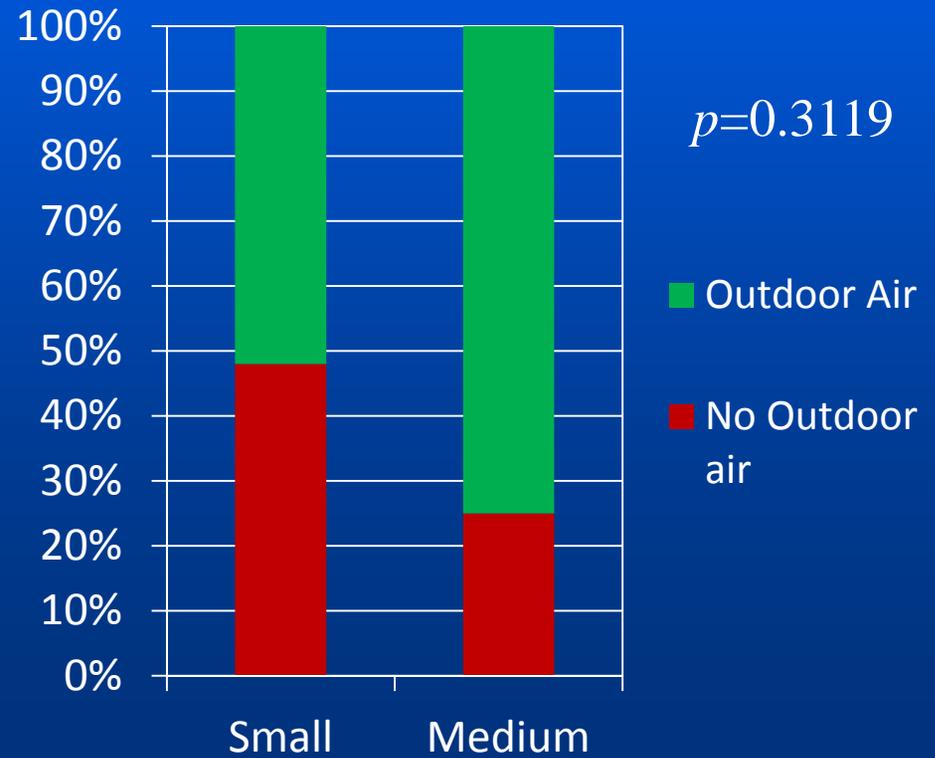
# Inspection Variables

- Inspected the following systems: Fans Working, Air Handling Units, Air Distribution Ductwork, Particulate Filtration System Components, Control System Components
- An overall score was created
  - Each variable averaged across all inspected units and normalized
  - Each part of the system averaged
  - Each system equally weighted to define overall score

# Buildings with No Mechanically Supplied Outdoor Air

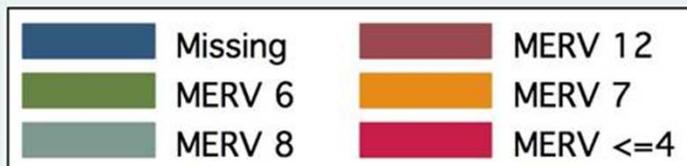
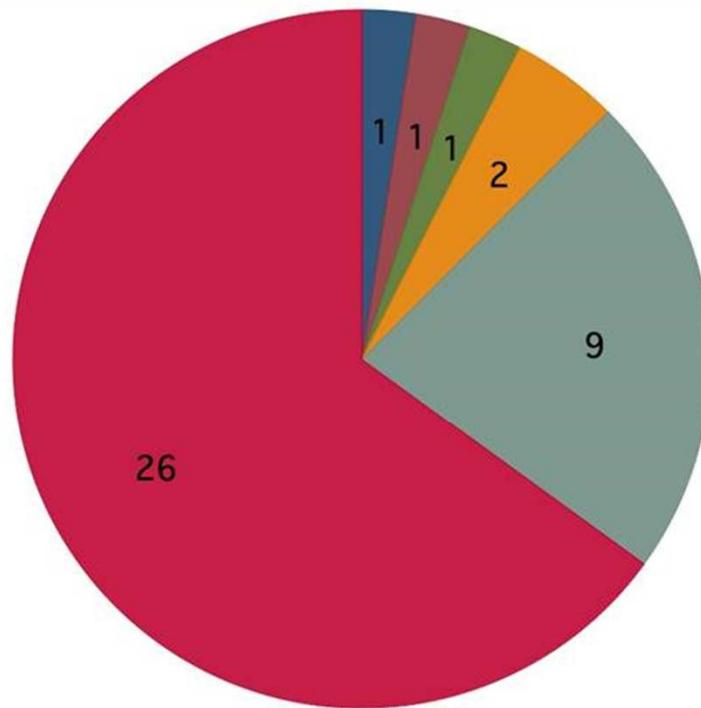


Retail also had high prevalence

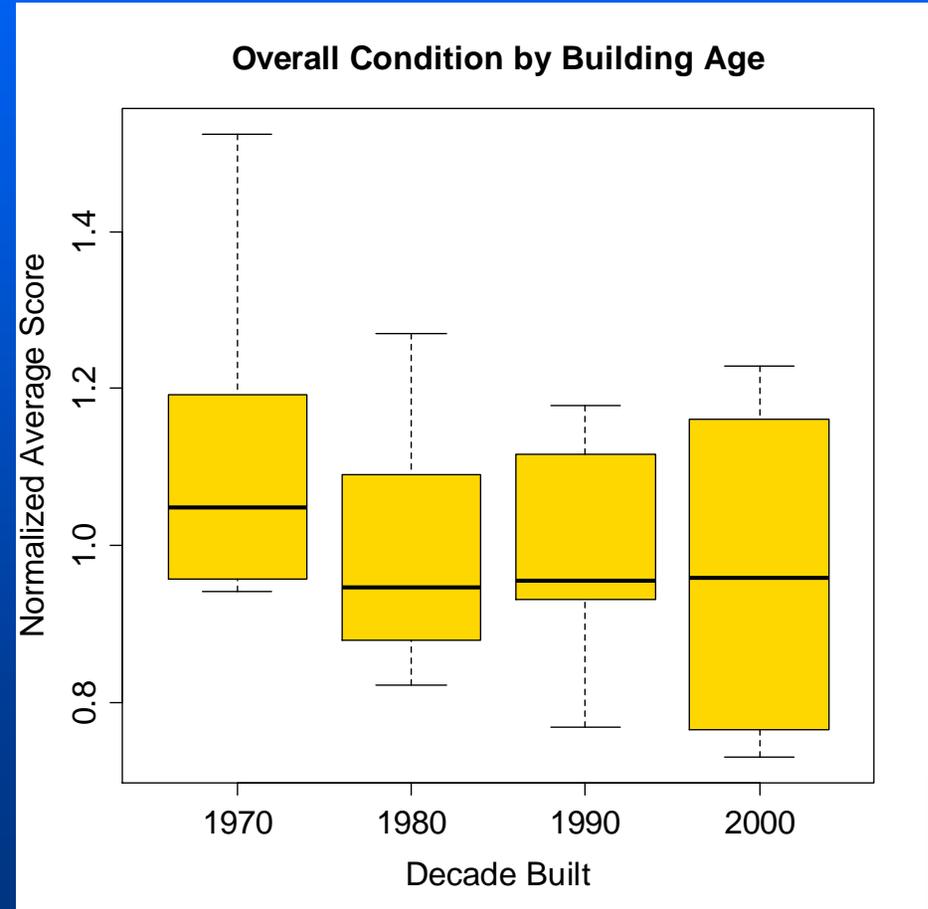
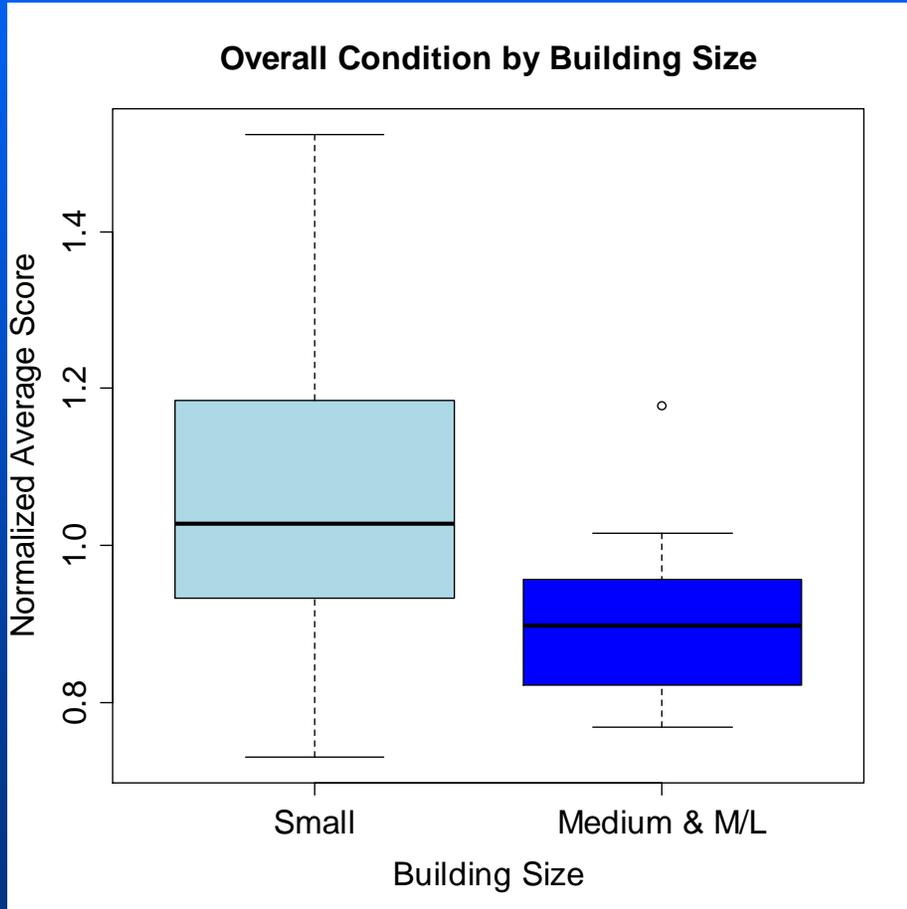


# Distribution of Filter Efficiencies

Observed Filter MERV Ratings in SMCB Field Study

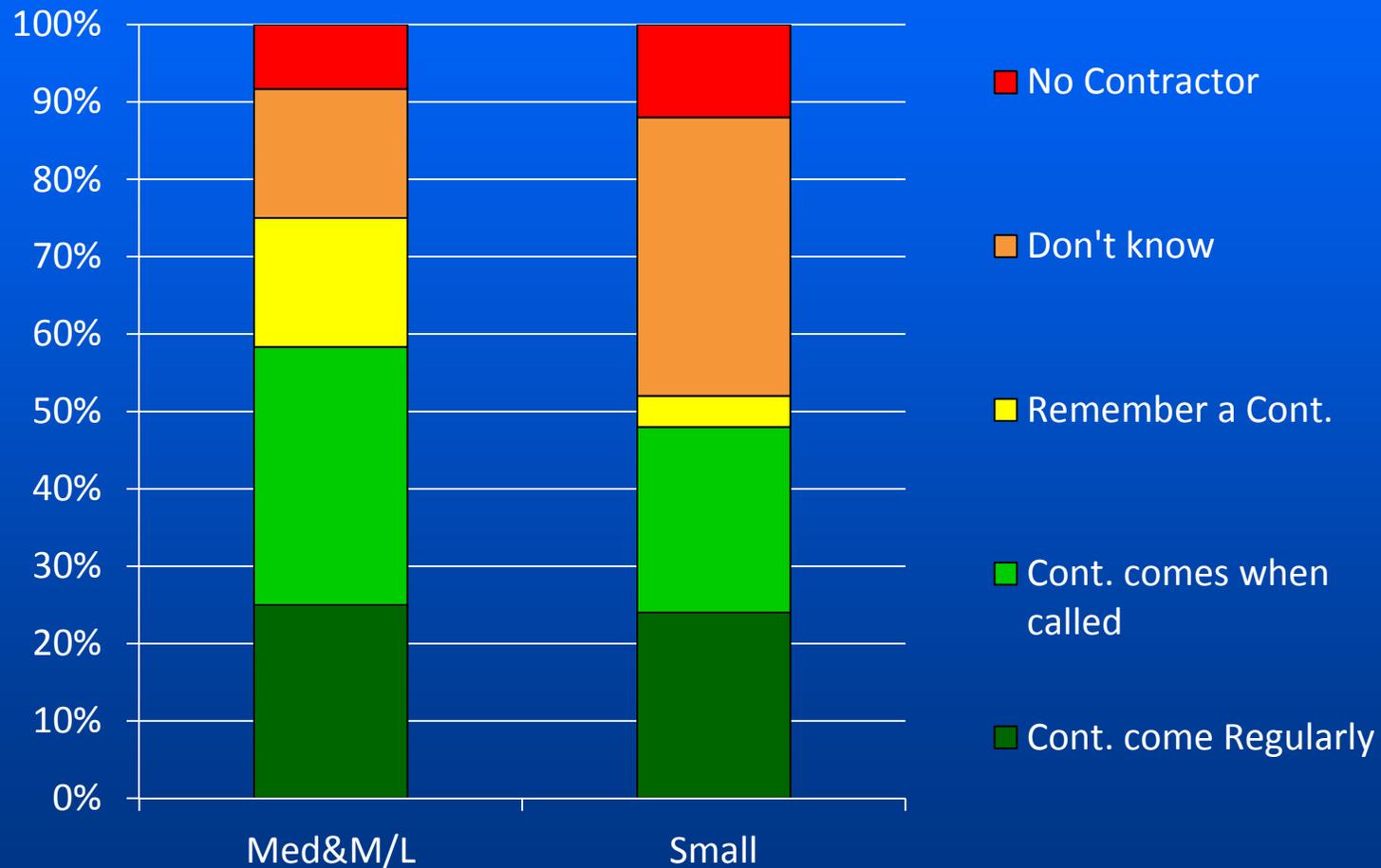


# Overall Condition by Building Size, Age

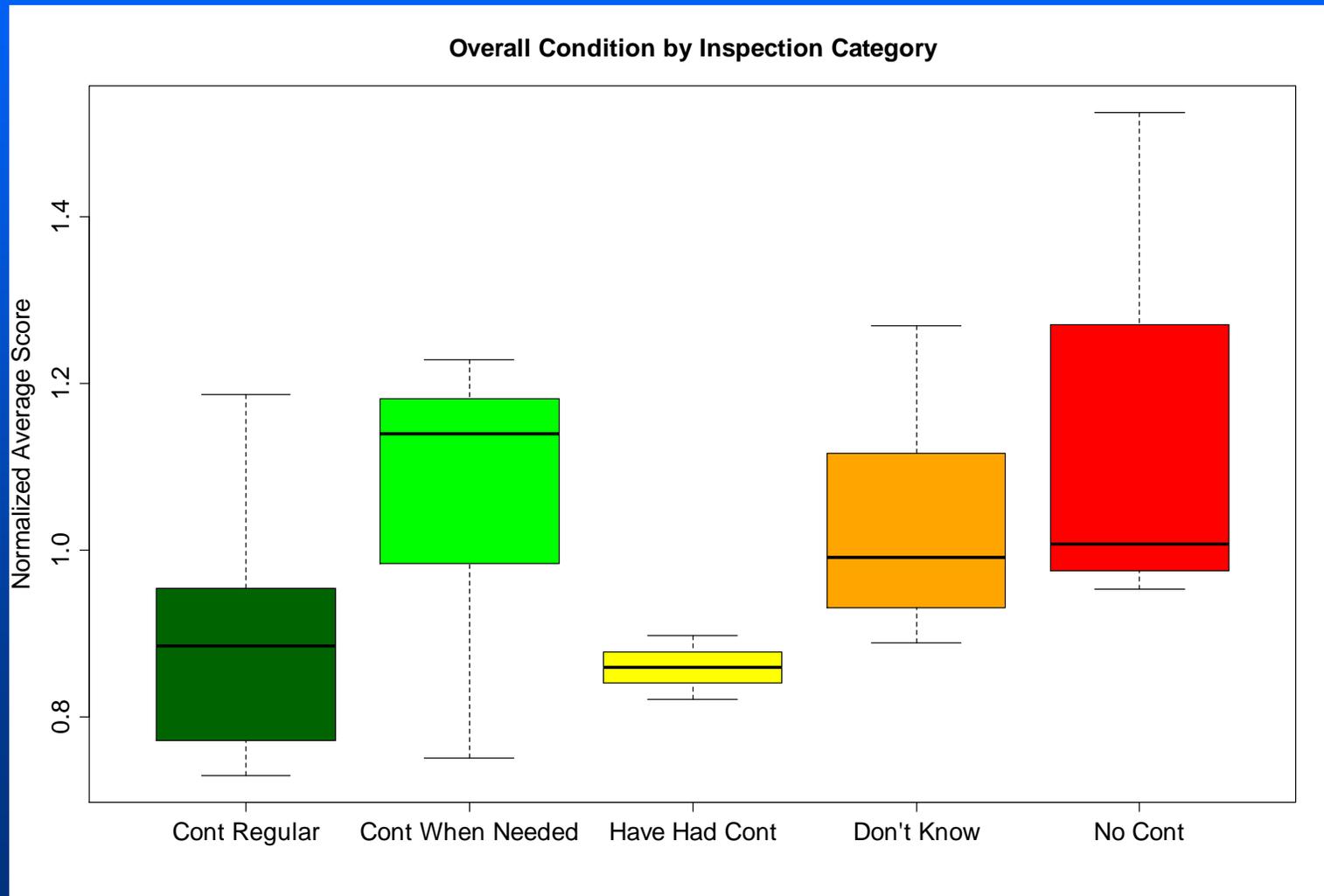


( $p=0.023$ )

# Do they have an HVAC contractor?



# Overall Condition by Maintenance Category



# Measurement of Air Exchange

- Whole Building Ventilation
  - PFT
  - Tracer Decay (Continuous Miran / grab bags)
  - CO<sub>2</sub> Equilibrium
- Total Mechanically Supplied Air
  - TRAMS
  - Supply Vent
- Outdoor Mechanically Supplied – Duct Blaster
- Fraction Outdoor Air – CO<sub>2</sub>

# Air Flow Rates

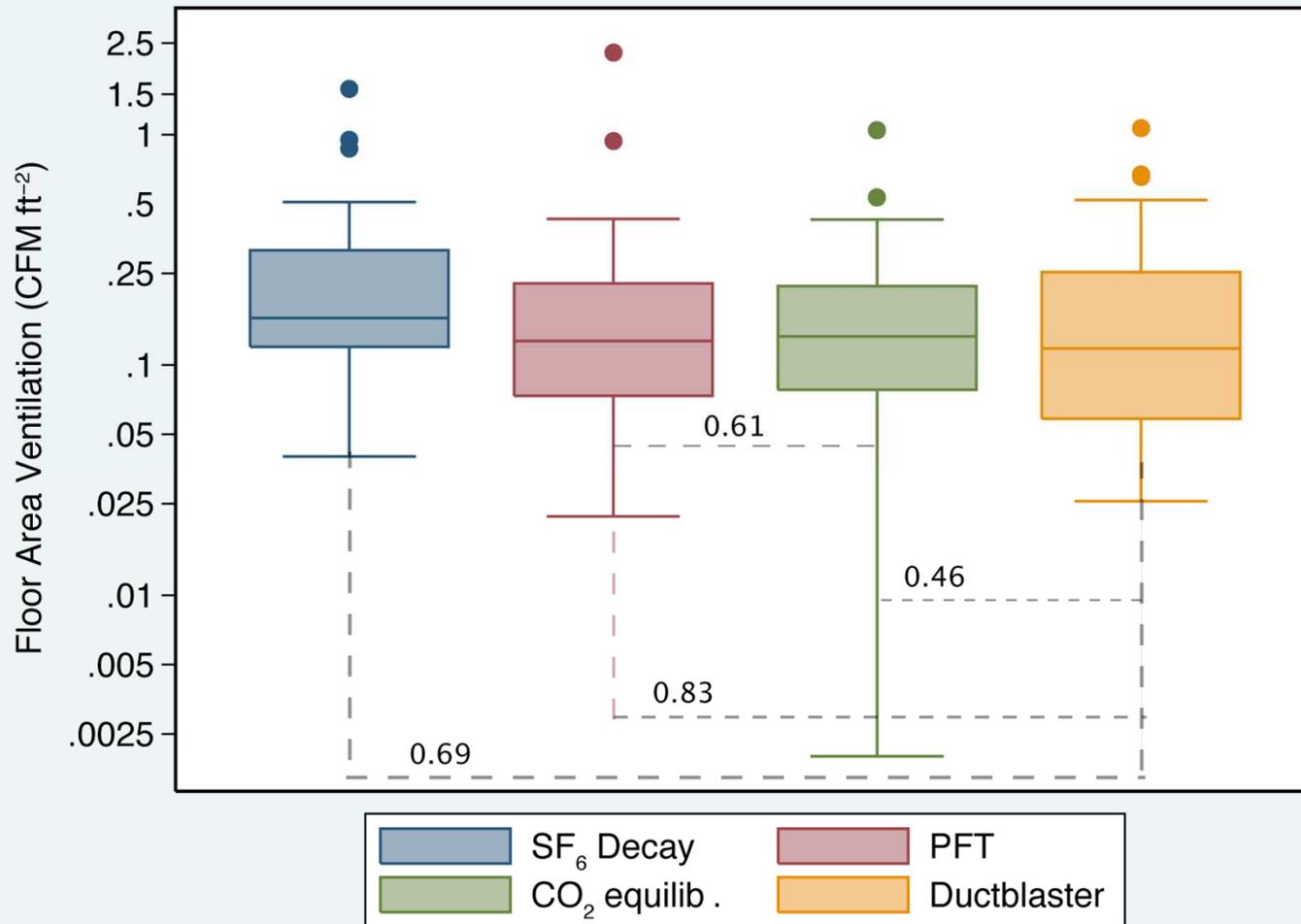
	N	Mean	SD	Median	Max
Air exchange rate, Steady-State (PFT) ( $\text{h}^{-1}$ )	40	1.03	1.08	0.73	6.26
Air exchange rate, Tracer Decay ( $\text{SF}_6$ ) ( $\text{h}^{-1}$ )	40	1.62	1.65	1.04	9.07
Whole-building ventilation rate (PFT) (cfm)	40	1245	2220	561	12434
Whole-building ventilation rate ( $\text{SF}_6$ ) (cfm)	40	1585	1951	980	10291
Whole-building ventilation rate per area ( $\text{SF}_6$ ) ( $\text{cfm}/\text{ft}^2$ )	40	0.27	0.27	0.19	1.51
Whole-building ventilation rate per person ( $\text{SF}_6$ ) (cfm/person)	40	130	151	76	680
Mechanic. supplied ventilation per area by TRAMS <sup>b</sup> ( $\text{cfm}/\text{ft}^2$ )	17	1.32	0.70	1.11	2.64
Outdoor air deliver rate by HVAC per area ( $\text{cfm}/\text{ft}^2$ )	40	0.13	0.23	0.04	1.07

# Fraction Outdoor Air

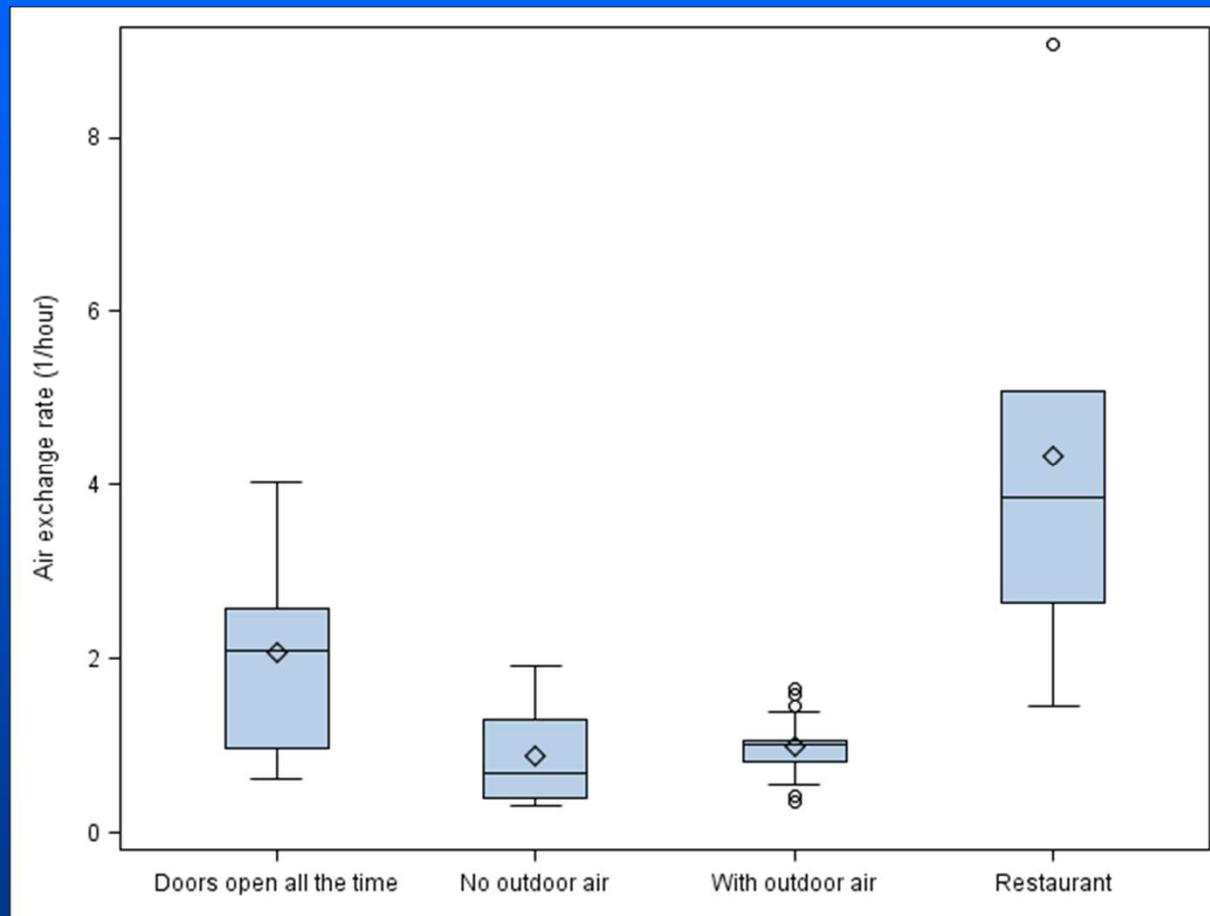
- In the ducts (not measured if no outdoor air intake)
- Fraction of outdoor air coming from mechanical system vs. infiltration/ natural ventilation
  - 16 had no OA, 9 had 100% OA

	N	Mean	SD	Median	Max
Calculated based on Duct Blaster and Tracer Decay method <sup>c</sup> (%)	14	45	26	47	82
Direct measurements by the CO <sub>2</sub> Ratio Method (%)	20	23	17	19	64

# Ventilation Method Comparison

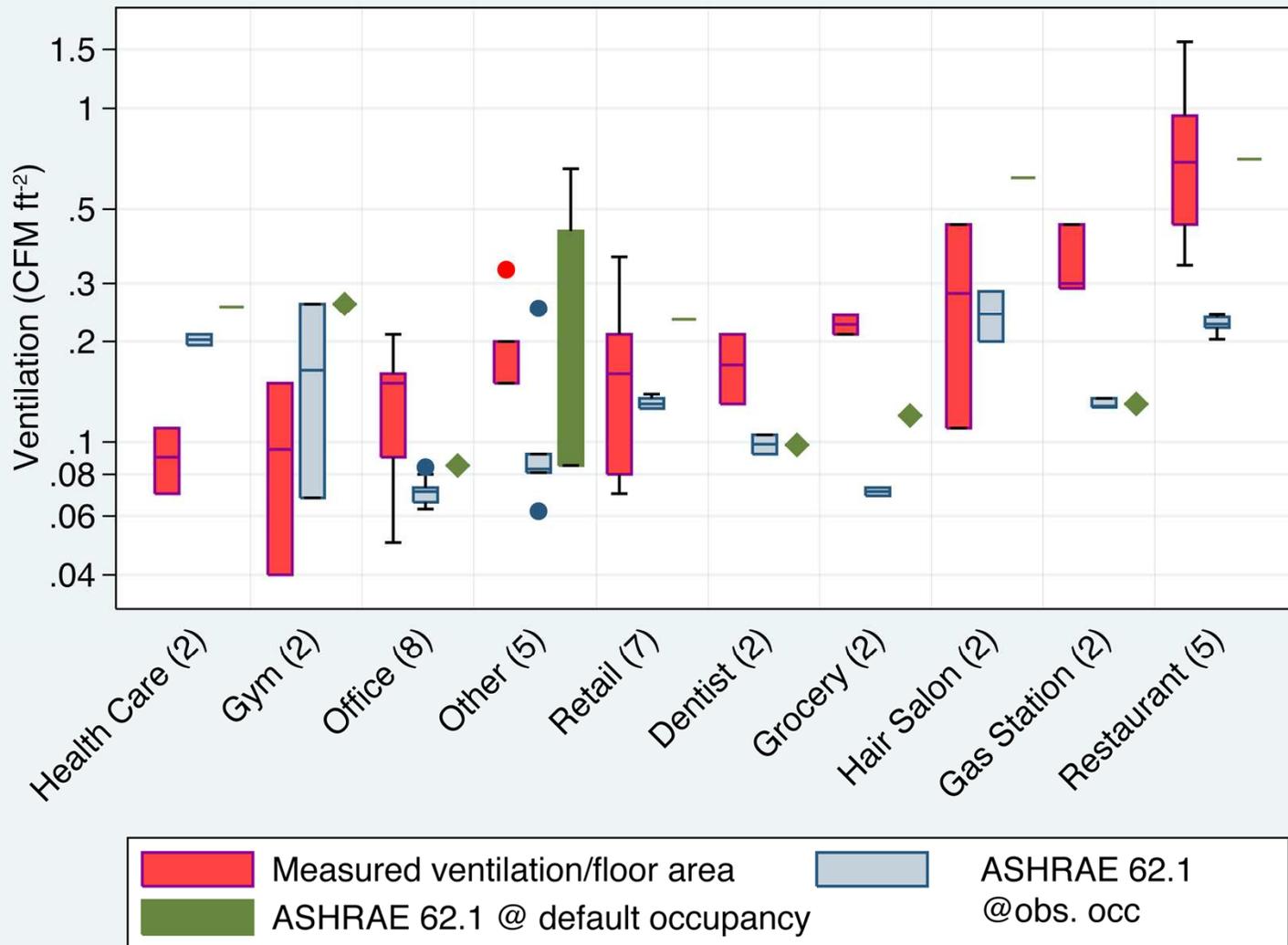


# Factors Influencing AER



\* Some of the buildings with doors open also had mechanically supplied outdoor air

# Specific Ventilation vs. Stds.



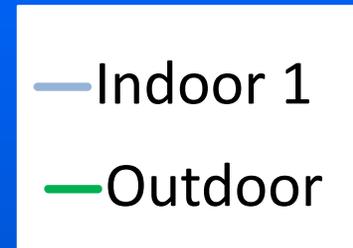
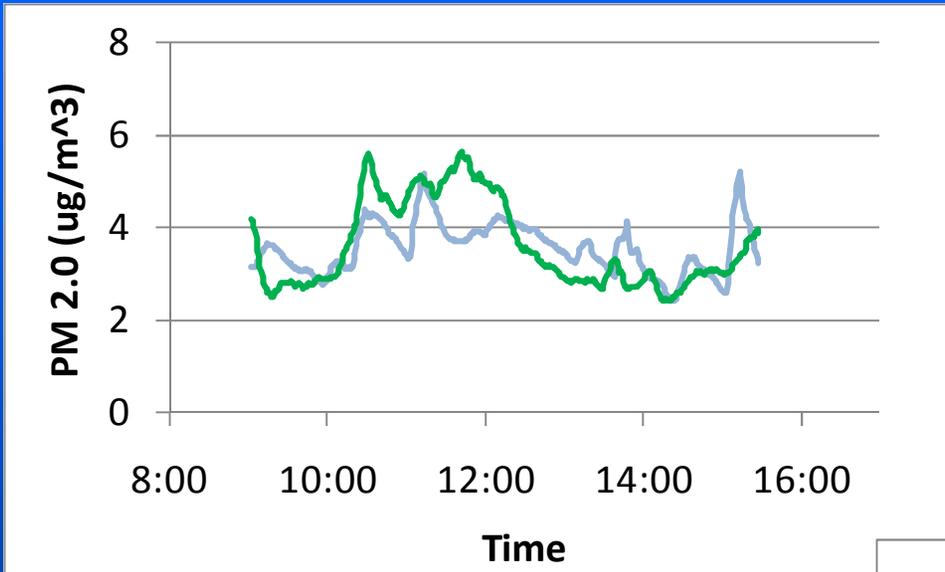
# Buildings with high CO<sub>2</sub>

- All buildings below health standards
- Three buildings exceeded ASHRAE 62.1
  - An office building
  - A busy gym
  - A busy hair salon
- Exceeded at the 75<sup>th</sup> percentile
  - A busy restaurant

# Particulate Matter Measurements

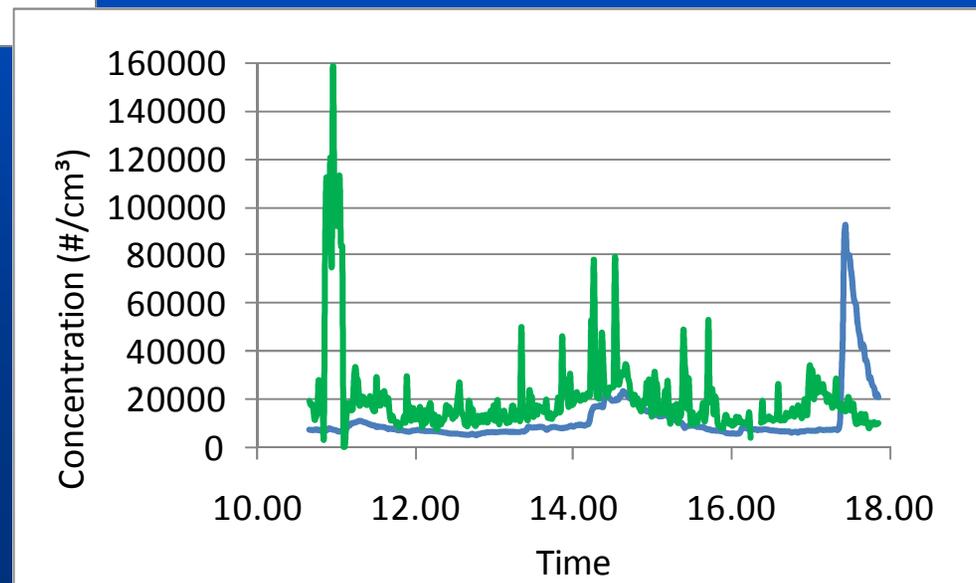
- Ultrafine Particles
  - Continuous 0.5 to 0.003  $\mu\text{m}$  count using TSI CPC Model 3781 sampler
- PM 2.5 and PM 10
  - Harvard cascading impactors
- Continuous size fractions under 2.0  $\mu\text{m}$ 
  - Met One optical particle counters

# Example of Building w/ Open Doors – Gas Station

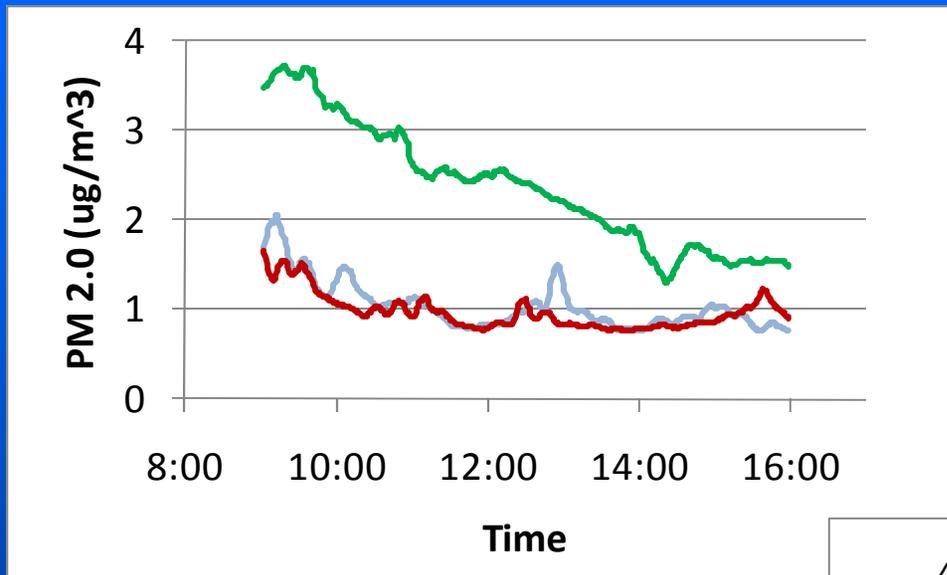


← PM 2.0

Ultrafine →

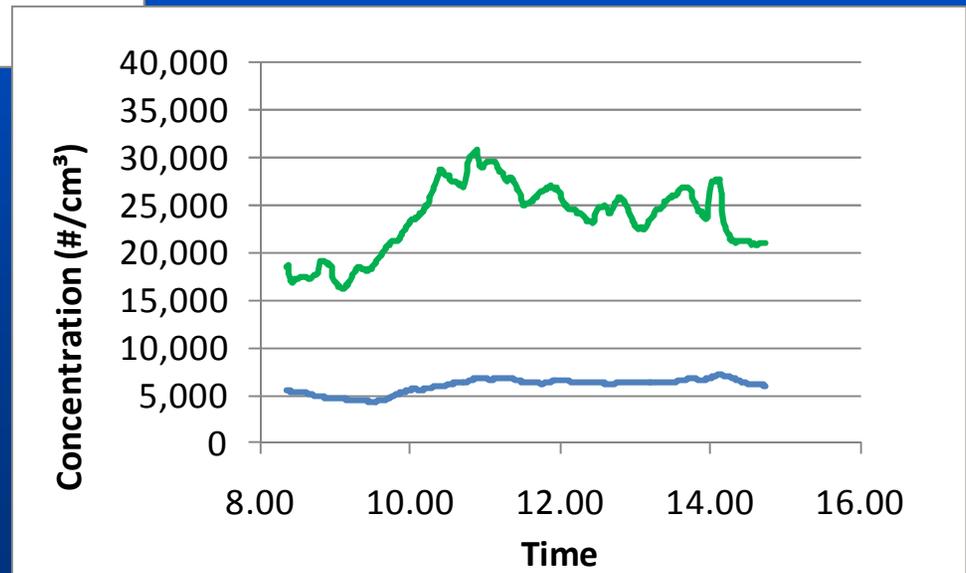


# Example of Efficient Filtration - Office

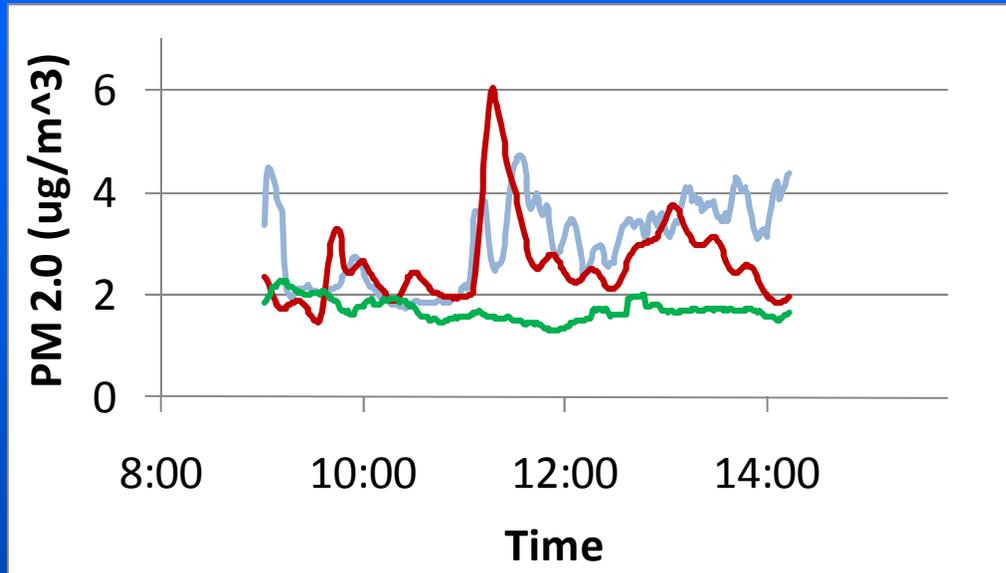


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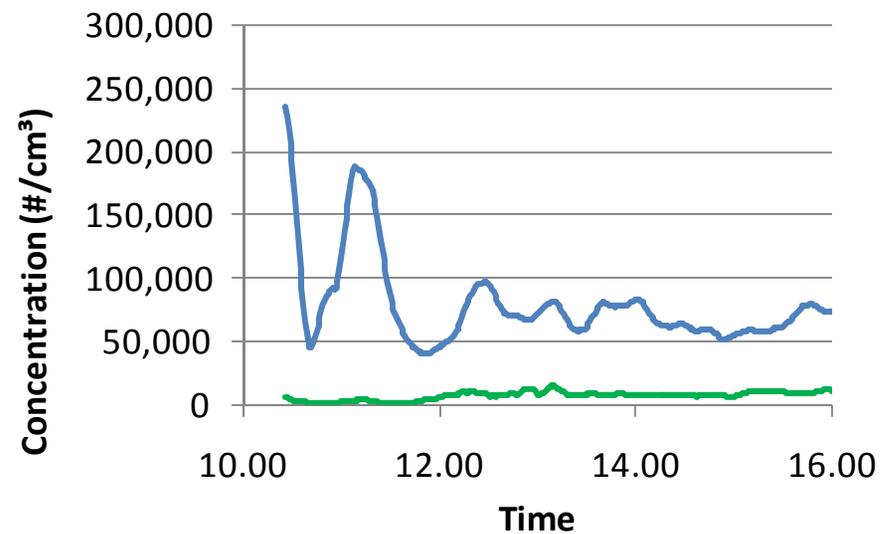


# Example of a Restaurant

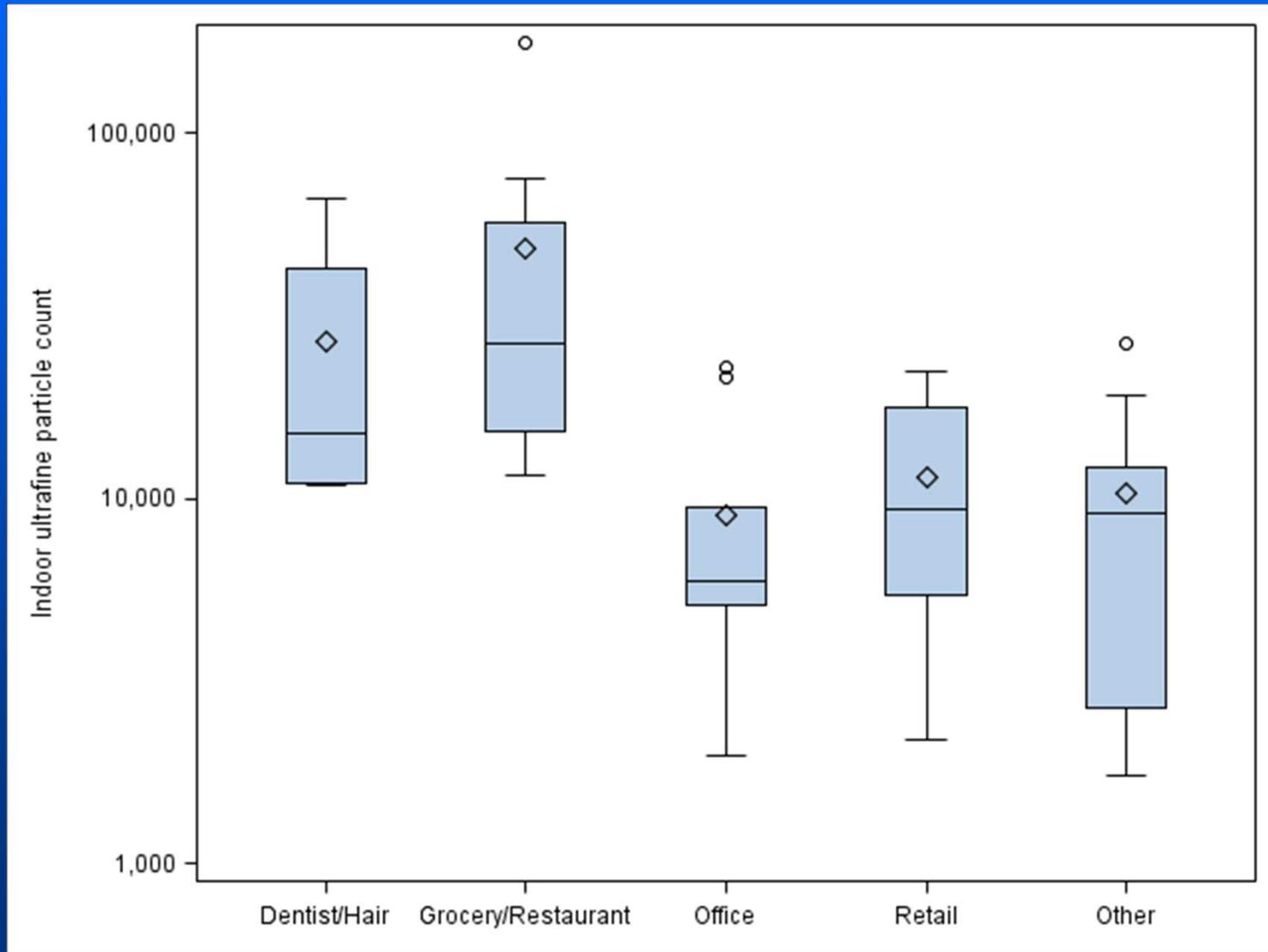


← PM 2.0

Ultrafine →



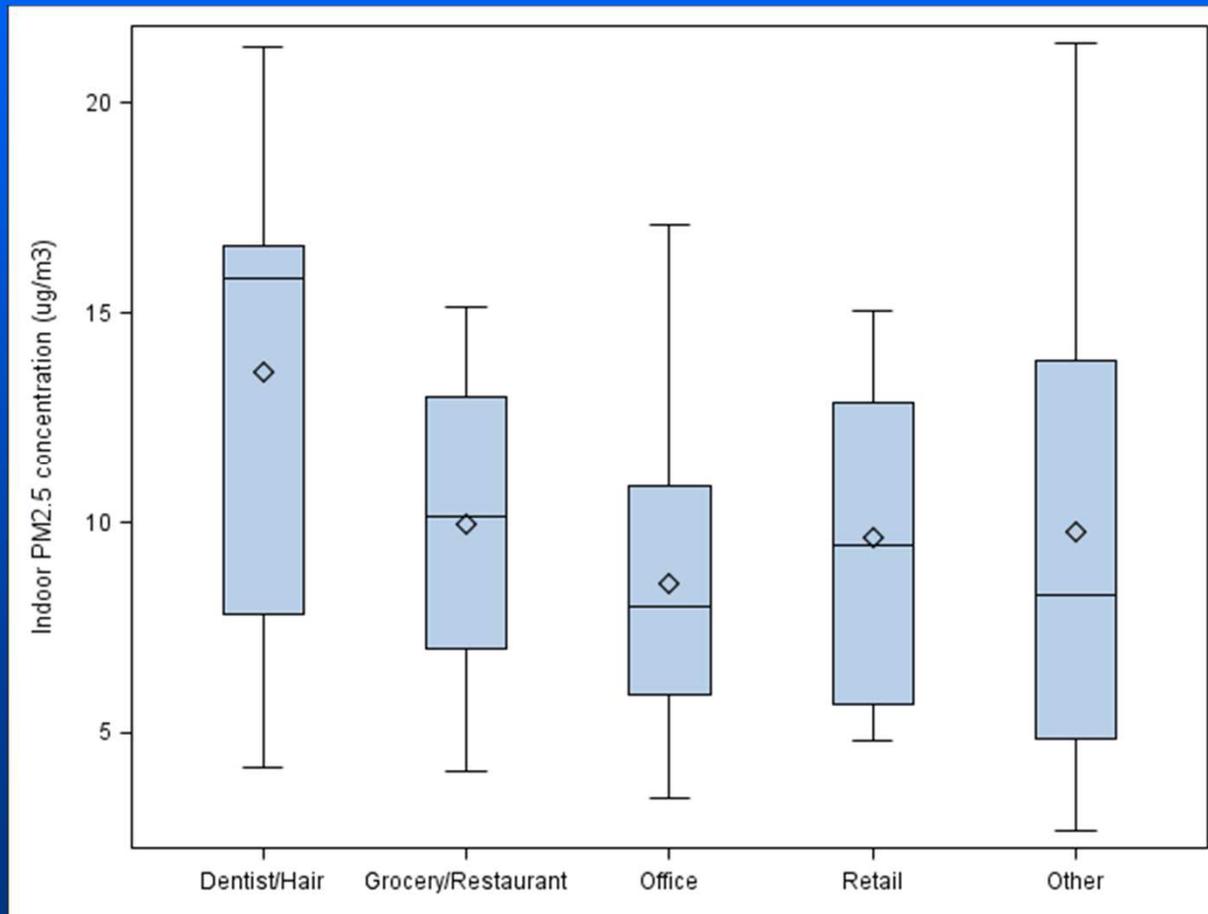
# Ultrafine Concentration Distributions



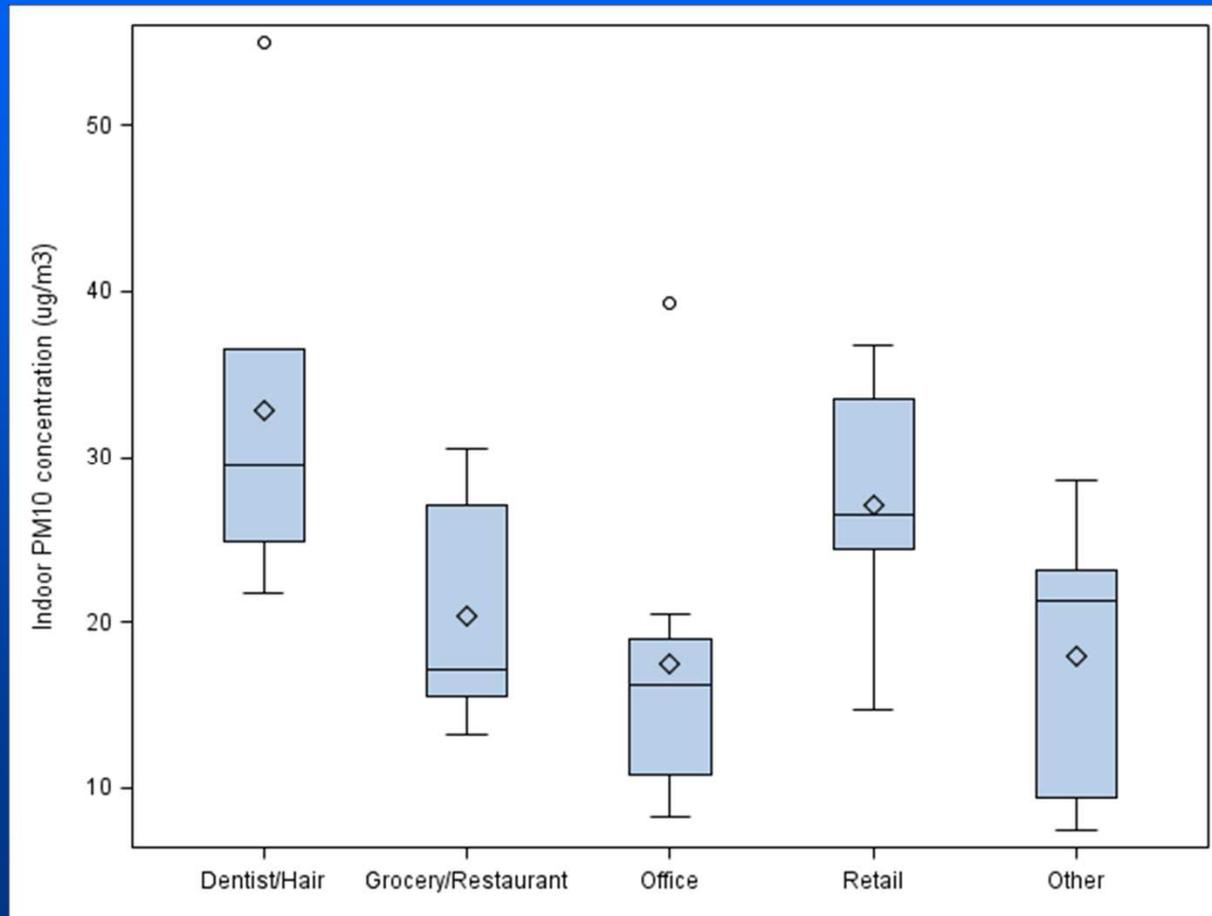
# PM 2.5 and 10 Concentration Distributions

		N	Mean	SD	25 <sup>th</sup> %	Median	75 <sup>th</sup> %	95 <sup>th</sup> %
PM <sub>2.5</sub>	I ( $\mu\text{g}/\text{m}^3$ )	39	10.06	4.94	5.89	9.43	13.76	21.34
	Outdoor ( $\mu\text{g}/\text{m}^3$ )	37	11.83	7.05	7.89	9.41	12.52	28.67
	I/O ratio	37	1.16	0.99	0.55	0.86	1.36	3.69
PM <sub>10</sub>	Indoor ( $\mu\text{g}/\text{m}^3$ )	38	22.39	9.98	15.53	22.12	27.75	39.35
	Outdoor ( $\mu\text{g}/\text{m}^3$ )	36	30.75	15.15	20.56	27.82	36.85	69.43
	I/O ratio	36	0.94	0.73	0.56	0.78	1.16	2.91

# PM 2.5 Concentration Distributions



# PM 10 Concentration Distributions

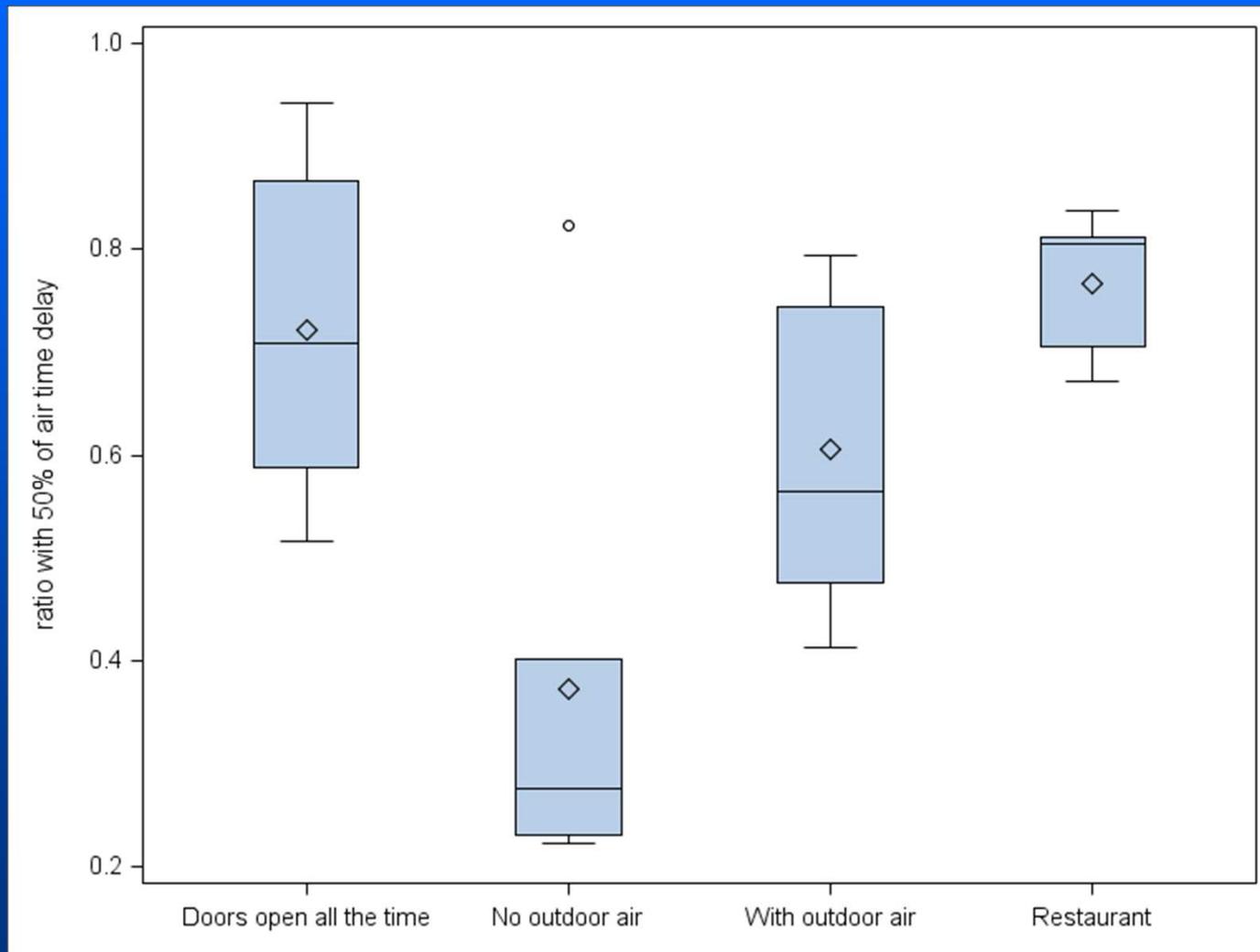


Offices have significantly lower concentrations,  $p=0.01$

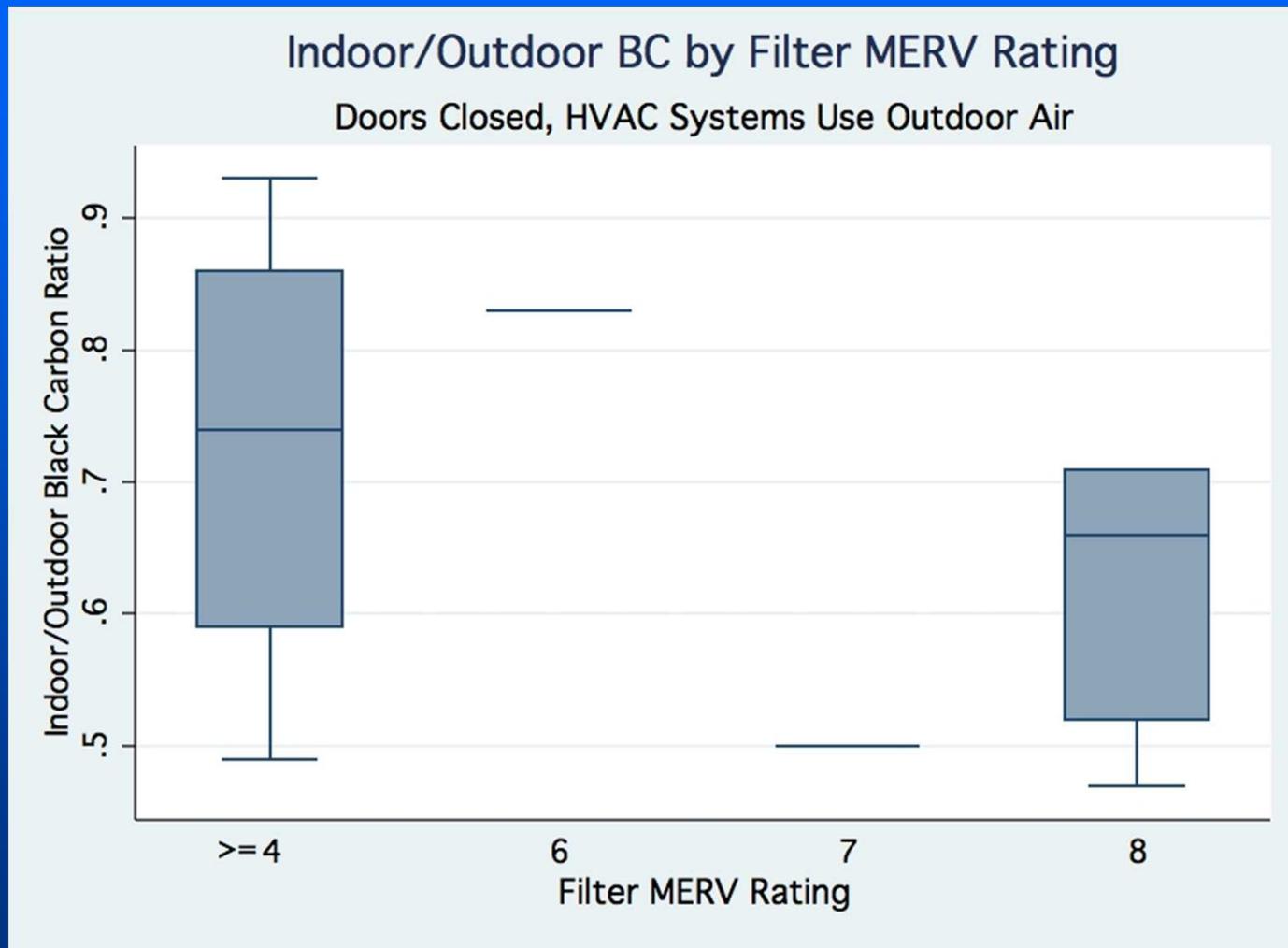
# Penetration Rates

- Estimate penetration rates using black carbon measures via aethelometers
- One aethelometer is on the roof, one is inside, and one is outside (street level)
- Rooftop generally has less fluctuations and is slightly lower than outside monitor
- The indoor generally tracks the rooftop levels if there is mechanically supplied outdoor air
- Selected rooftop or outdoor based on whether 50% of the air was likely to enter building mechanically

# Box plots of I/O black carbon



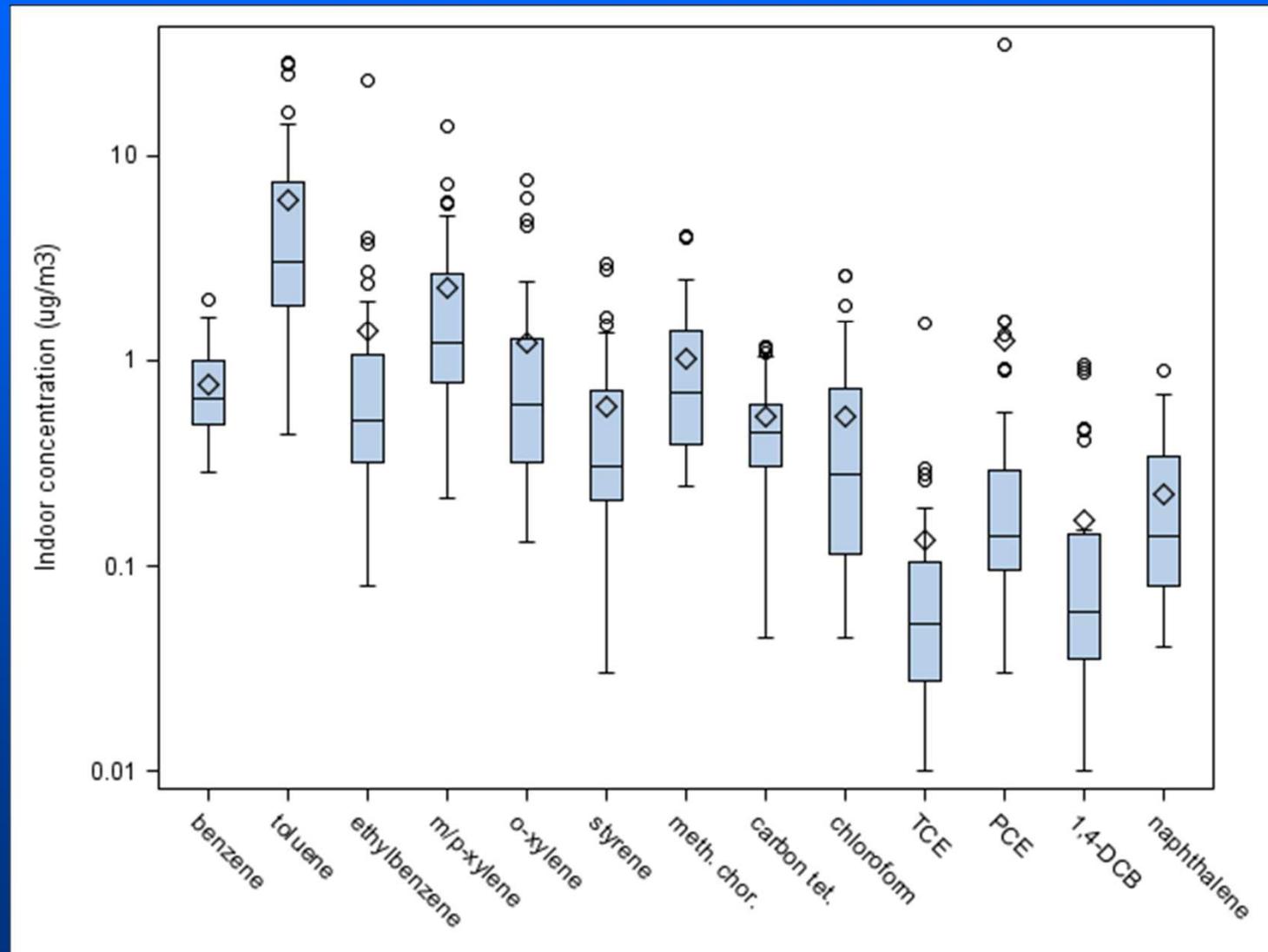
# I/O ratio vs filter efficiency



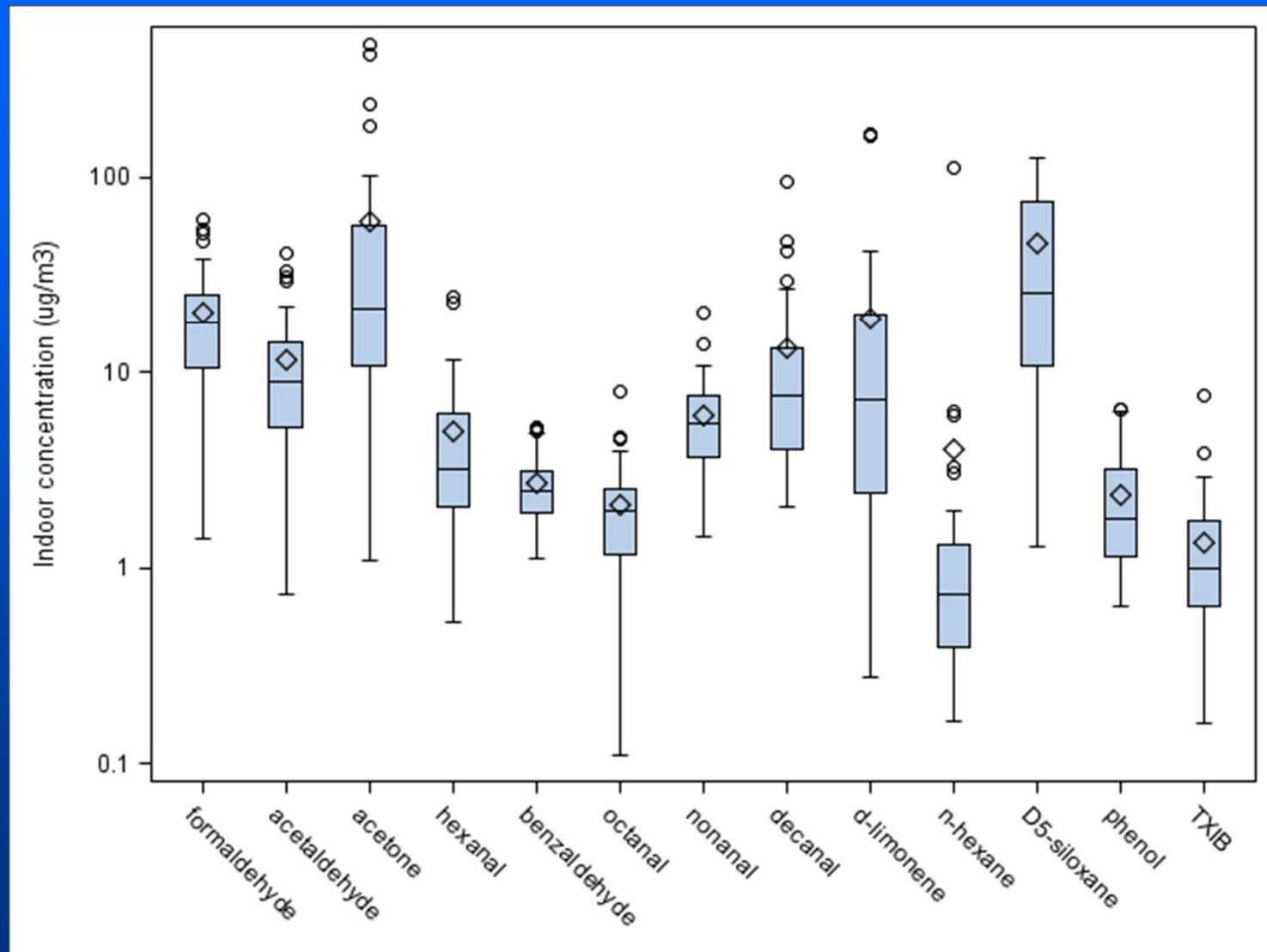
# Toxic Air Contaminants

- “Typically Measured” compounds
  - benzene, toluene, ethylbenzene, m/p-xylene, o-xylene, C.Tet., methylene chloride, TCE, PCE, chloroform, styrene, formaldehyde, acetaldehyde, acetone
- Thought to have indoor sources
  - naphthalene, 1,4-dcb, phenol, 2-butoxy ethanol
- Involved in indoor chemistry and indoor sources
  - a-pinene, d-limonene, a-terpineol, benzaldehyde, nonanal, deconal, and octanal
- Other compounds of interest
  - D5-siloxane, diethylphthalate, hexanal, TXIB

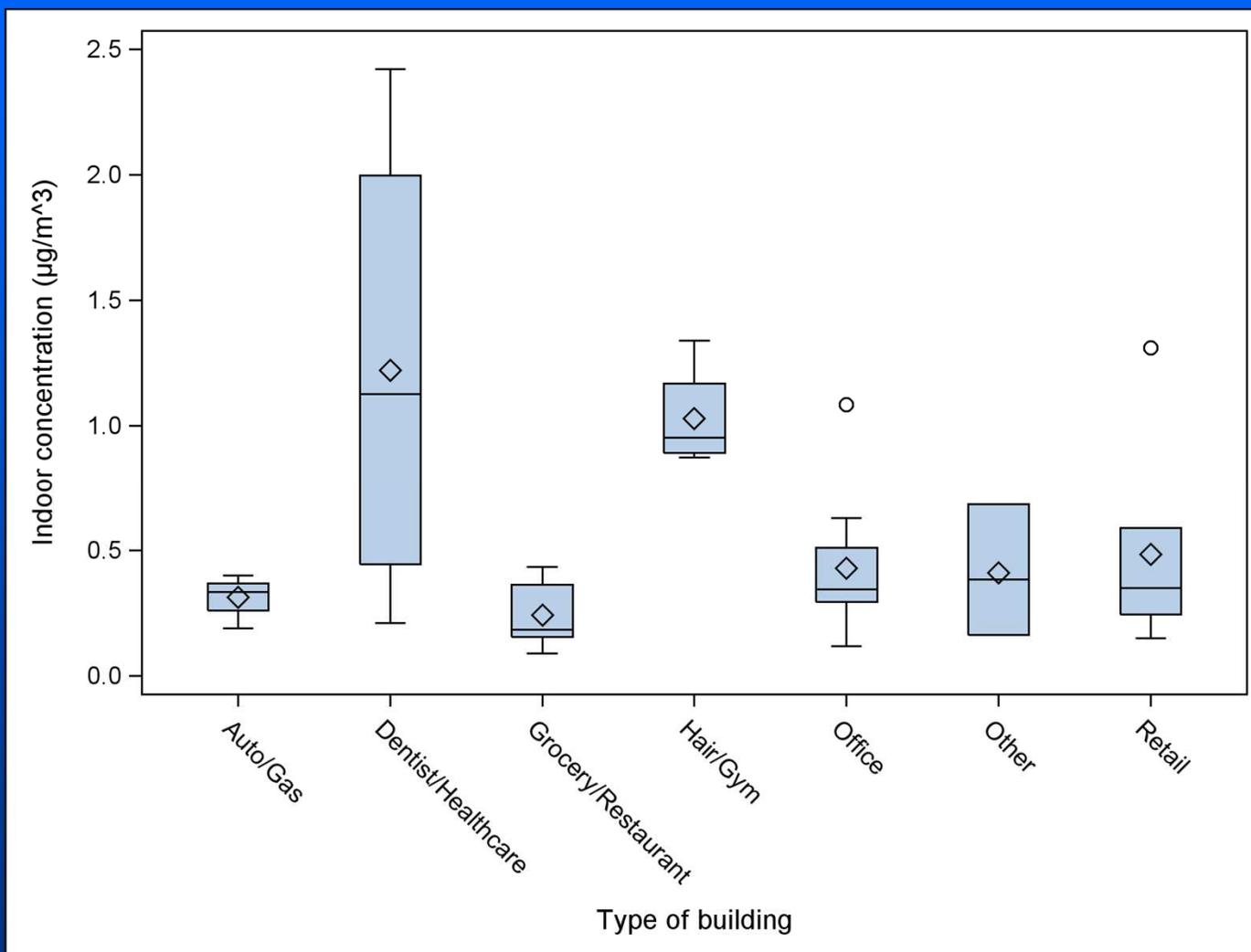
# VOC Concentration Distribution



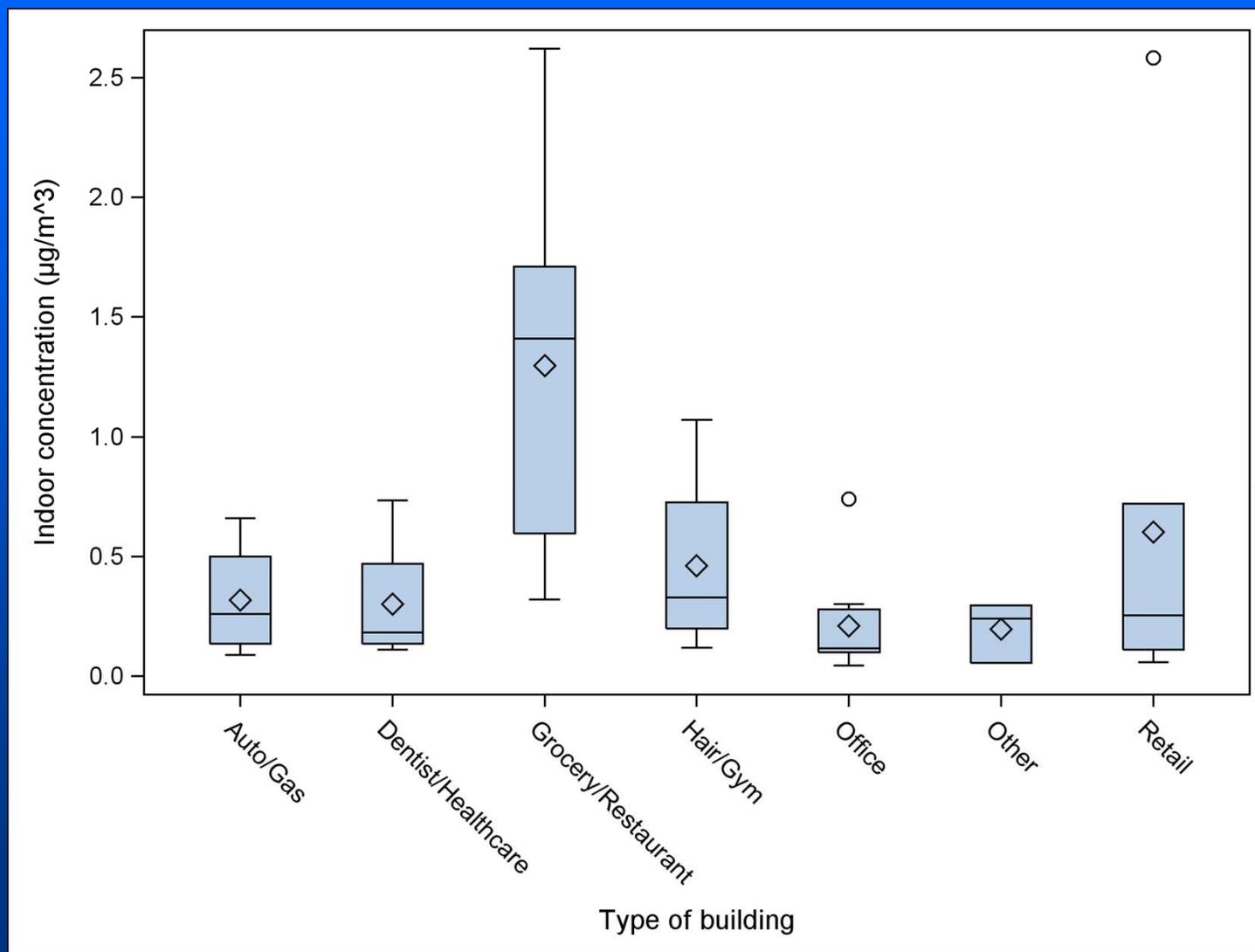
# VOC Concentration Distribution



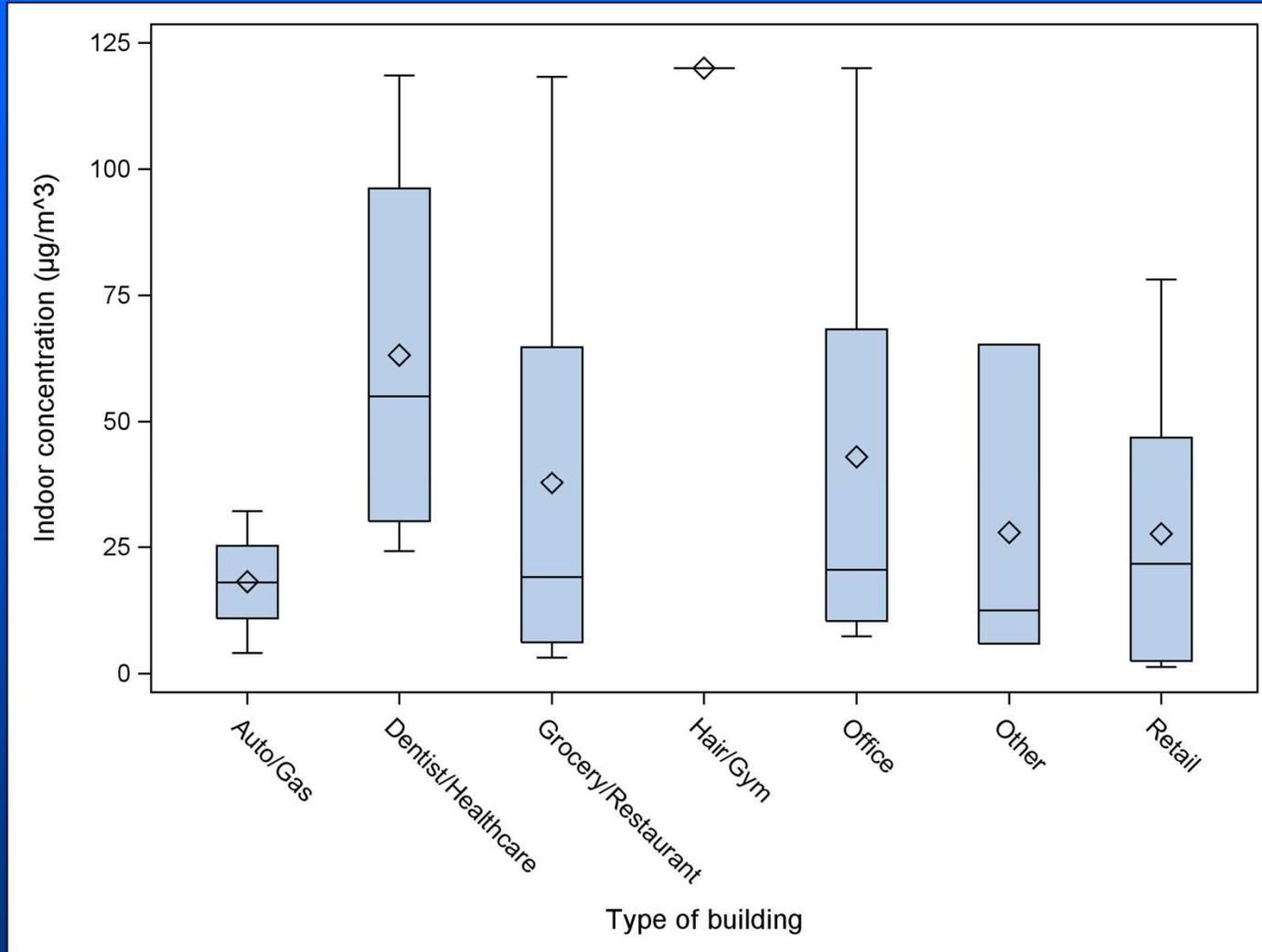
# Diethylphthalate



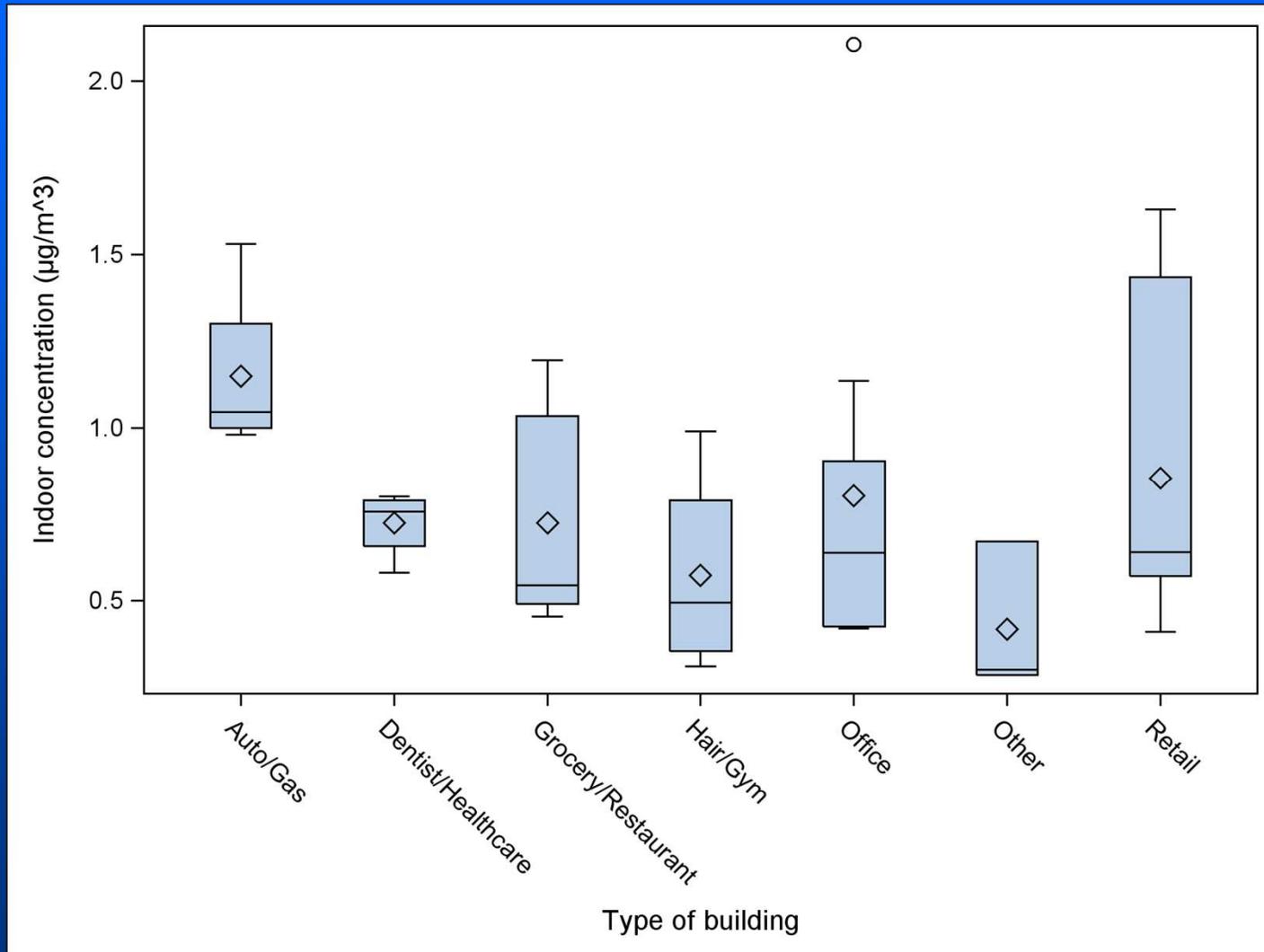
# Chloroform



# D5-siloxane



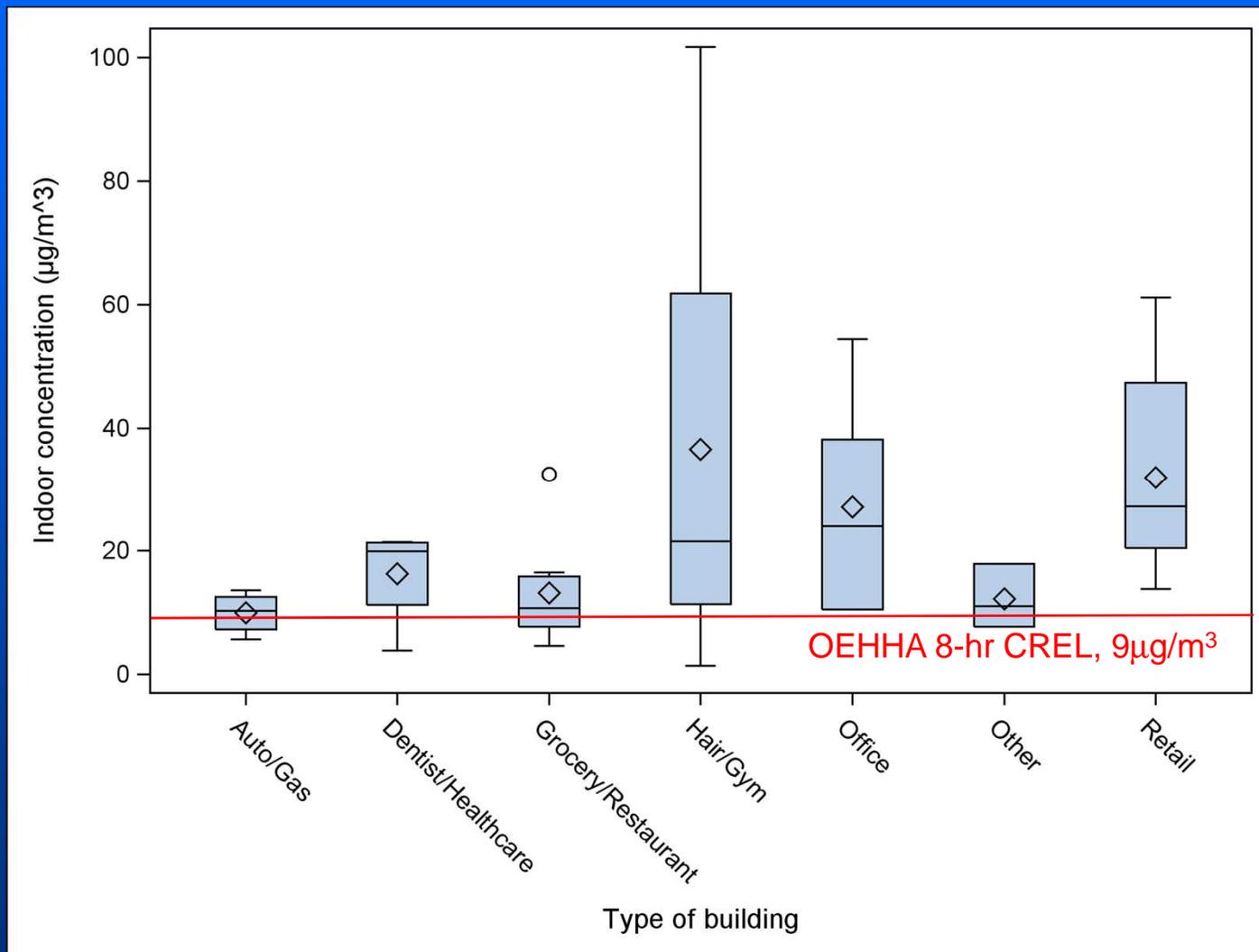
# Benzene



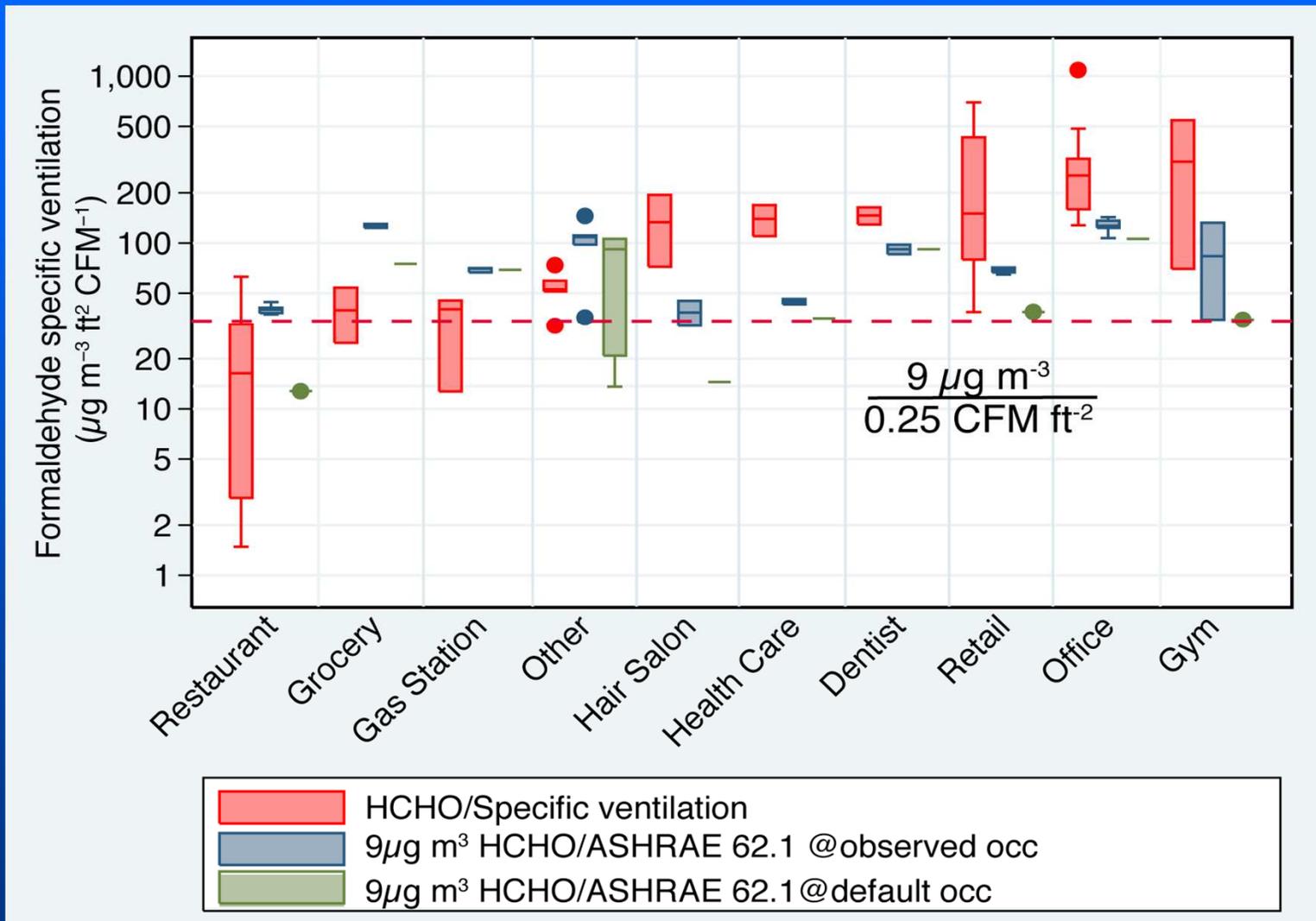
# Elevated Levels in One Building Type

- acetaldehyde – Grocery/ Restaurant
- acetone, ethylbenzene, o-xylene, n-hexane – Dentist/ Healthcare
- methylene chloride, benzene – Auto/Gas
- D5-Siloxane – Hair/Gym
- a-pinene, octanal, toluene – Retail
- Phenol - offices

# Formaldehyde



# Ventilation of Formaldehyde



## Impact of the Presence of Carpet and Wood Furniture on Indoor Formaldehyde Concentration

Category		N	Mean ( $\mu\text{g}/\text{m}^3$ )	Comparison <sup>a</sup>
Any carpet present	Y	26	23.3	$p=0.007$
	N	10	14.2	
Primary flooring is carpet	Y	22	24.5	$p=0.01$
	N	15	14.8	
New carpet is primary floor covering	Y	5	16.3	$p=0.6$
	N	33	20.9	

<sup>a</sup> The comparison is based on log transformed indoor concentration of formaldehyde, using analysis of variance.

# Factor Analysis of VOCs

Compound	Factor				
	1	2	3	4	5
Benzene	0.87	.	.	.	.
Toluene	0.70	.	.	.	.
Ethylben	0.65	.	.	.	.
Formaldehyde	.	.	.	.	0.77
Acetaldehyde	.	.	.	.	0.73
Octanal	.	.	0.75	.	.
Nonanal	.	.	0.81	.	.
Decanal	.	.	0.61	.	.
d-limonene	0.35	0.55	.	.	.
$\alpha$ -terpineol	.	0.69	.	.	.
n-hexane	0.78	.	.	.	.
D5-siloxane	.	0.78	.	.	.
TXIB	.	.	.	0.74	.
DEP	.	.	.	0.69	.

Note: The analysis includes 62 observations and 14 variables. Factor loadings shown are after an oblique rotation and an orthogonal VARIMAX rotation. Factor loadings greater 0.30 in absolute value are shown and loadings greater than 0.50 are considered to be significant.

# Conclusions

- Lack of mechanically supplied outdoor air
- Poorly maintained systems, problems with filters
- HVAC systems tend to be better maintained in newer and larger buildings
- Buildings mainly met ventilation standards
- Some buildings ventilated significantly above required levels, particularly restaurants
- Elevated indoor concentrations measured in expected building types
- Need to think more about formaldehyde
- Particles well filtered through building shell

# Recommendations

- More efficient filters
- Products that emit less formaldehyde
- Training should be provided regarding the HVAC system when building ownership is transferred or a lease signed
- Recommissioning of HVAC systems at point of sale or at fixed year intervals
- Improve inspection process of new HVAC systems of existing buildings
- Stricter verification of code compliance for commissioning of new buildings

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