The Effect of Smoke from Burning Vegetative Residues on Airway Inflammation and Pulmonary Function in Healthy, Asthmatic, and Allergic Individuals

Colin Solomon Ph.D., John Balmes, MD.
Lung Biology Center
University of California, San Francisco

Bryan Jenkins, Ph.D.
Department of Biological and Agricultural Engineering
University of California, Davis

Michael Kleinman, Ph.D.
Department of Community and Environmental Medicine
University of California, Irvine

Introduction

- It is common practice worldwide to use open field burning for the clearance of agricultural fields.
- Burning reduces the high costs involved in both removing the crop residue post-harvest, and for pest and disease control.
- Rice is a major crop in California, particularly in the Central Valley region.
- There is concern that open field burning and subsequent smoke exposure in humans could result in adverse health effects.

Introduction

- When incorrect predictions (weather forecasts), or changes, in climatic conditions (wind direction, temperature inversions) occur, rice straw smoke (RSS) moves into inhabited areas.
- RSS contains potentially biologically toxic airborne respirable particles and gases.
  - Particles; carbon (C), nitrogen (N), sulfur (S)
  - Gases; carbon-monoxide (CO), carbon-dioxide (CO_2), oxides of nitrogen (NO_x).
- Currently, there is no specific data on the direct effect of RSS exposure on respiratory health.

Introduction; Epidemiology

- In Butte County, California, 1983-1992:
  - 690,000 acres of rice straw was burned (82% of the total planted acreage).
  - Maximum concentration of airborne particulate matter with a mean mass aerodynamic diameter (MMAD) < 10 mm (PM_{10}), was 636 $\mu g\ m^3$.
  - There was a significant increase in the risk for hospitalization, and asthma morbidity (Jacobs *et al.* 1997).

Introduction; Epidemiology

- In Winnipeg, Canada, October 1992:
  - RSS episode elevated levels of PM_{10}, to 200 μg m^3, and elevated carbon monoxide, nitrogen dioxide, and volatile organic compounds (VOC).
  - In individuals with airway obstruction and airway hyper-reactivity; 42% had onset or worsened cough, wheezing, chest tightness, or shortness of breath, and 20% had trouble breathing during the episode.
  - Individuals with asthma or chronic bronchitis were most likely to be effected (Long *et al.* 1998).

Introduction; Epidemiology

- In Niigata Prefecture, Japan, 1994 to 1998:
  - RSS elevated PM_{10} to 410 $\mu g\ m^3$.
  - There was an increase in the number of asthma attack visits to the emergency room, and asthma attack hospital admissions in children.
  - There was also a significant correlation between the ambient concentration of PM_{10}, and the number of asthma attacks in children (Torigoe *et al.* 2000).

Introduction; Epidemiology

- In Isfahan, Iran, October 2000:
  - RSS episode resulted in total particulate and PM_{10} being doubled.
  - There was an increase in recent asthma attacks, asthma medication use, sleep disruption due to dyspnea and cough, exercise-induced cough, and a decrease in pulmonary function (Golshan *et al.* 2000).

Introduction; Occupational

- California rice farmers reported chronic cough which was associated with hours per year engaged in burning rice stubble
- Rice farmers, compared to the general population, had an increased prevalence of asthma (McCurdy *et al.* 1996).

Introduction

- Epidemiological data indicate presence of RSS-induced respiratory health effects, and larger effects in individuals with respiratory disease.
- No controlled exposure or airway inflammation data in humans.
- Therefore, we designed controlled human exposure experiments to investigate the effects of RSS smoke exposure on airway inflammation in healthy, asthmatic, and allergic individuals.

Hypothesis

- Increased RSS concentration and dose would;
  - Increase airway inflammation (cells, proteins).
  - Decrease pulmonary function (volumes, flows)

- Pre-existing airway inflammation (asthma and allergic rhinitis), would result in increased RSS-induced changes in;
  - Airway inflammation
  - Pulmonary function

Method; Design

- Three controlled human exposure experiments.
  - Healthy subjects
  - Asthma subjects
  - Allergic-Rhinitis subjects
- Single-blind, repeated-measures, randomized.
- Exposure Chamber (control conditions).
- RSS generation and exposure system (UCD).

Rice Straw Smoke Generation System Design

University of California, Davis
Department of Biological and Agricultural Engineering
B.M. Jenkins, J.J. Mehlschau, R.B. Williams, N. Smith

University of California, San Francisco
Department of Medicine
C. Solomon, J. Balmes

University of California, Irvine
Department of Community and Environmental Medicine
M. Kleinman

California Air Resources Board

Details in Aerosol Science and Technology 37(5):437-454, 2003

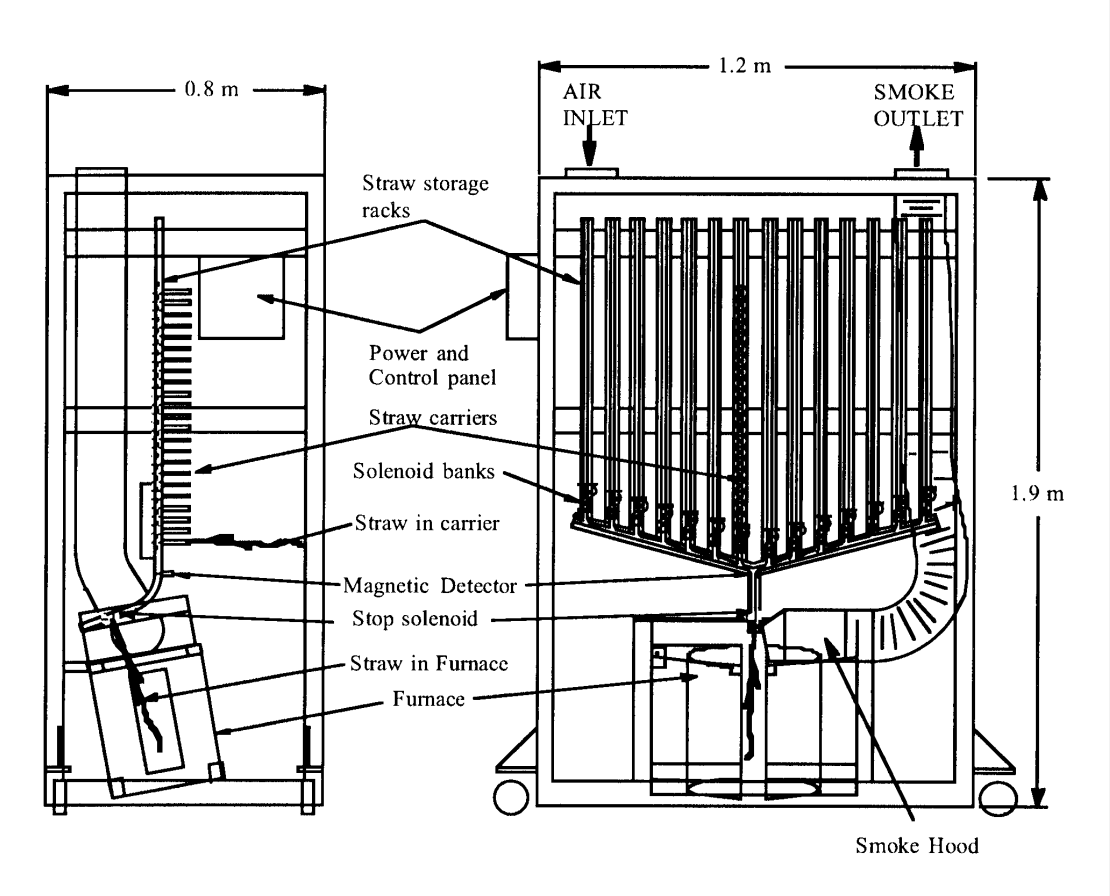
Design Objectives

- Mean particle concentrations of 200 to 600 $\mu g\, m^{-3}$ with good repeatability
  - (900 $\mu g\, m^{-3}$ achieved, 160 to 500 $\mu g\, m^{-3}$ used)
- Automatic operation for exposures ranging 30 min to 3 hours in duration
- Maintain temperature and relative humidity in exposure chamber (20°C, 50%)
- Match field conditions as much as possible (high air-fuel ratio, flame radiation).
- Residence time to approach equilibrium gas-particle partitioning for PAH (3-5 s within 20 K of ambient)
- Not to exceed exposure limits for gases, particularly CO, CO_2.
- Low level exhaust to street (SFGH location).

Rice Straw Characteristics

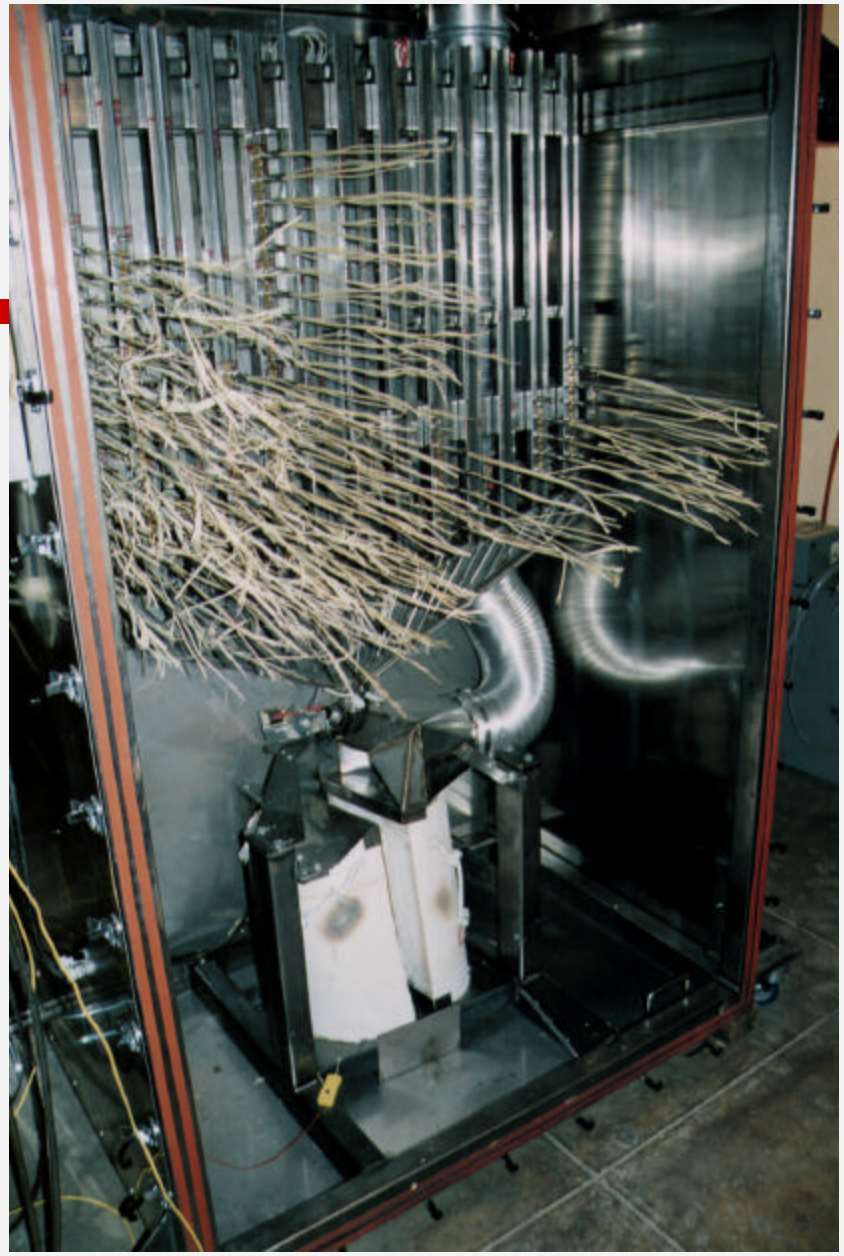
- Stipulated by CARB (Carnahan to Holmes,1998)
- M202 (medium grain Japonica, >50% of California production)
- Standard fertilization practice
- Average yield
- Collected from center of fields to minimize road dust
- No stipulations on moisture content, K, Cl, stem fraction

Singulated-Straw/ Shuttle-in-Rack Design

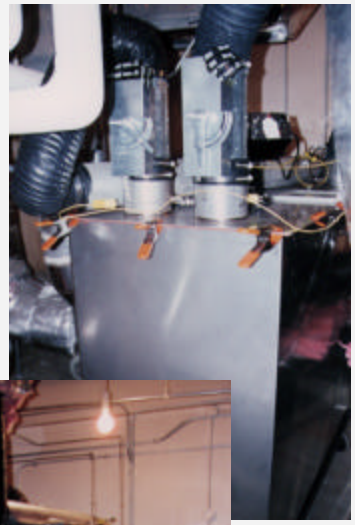


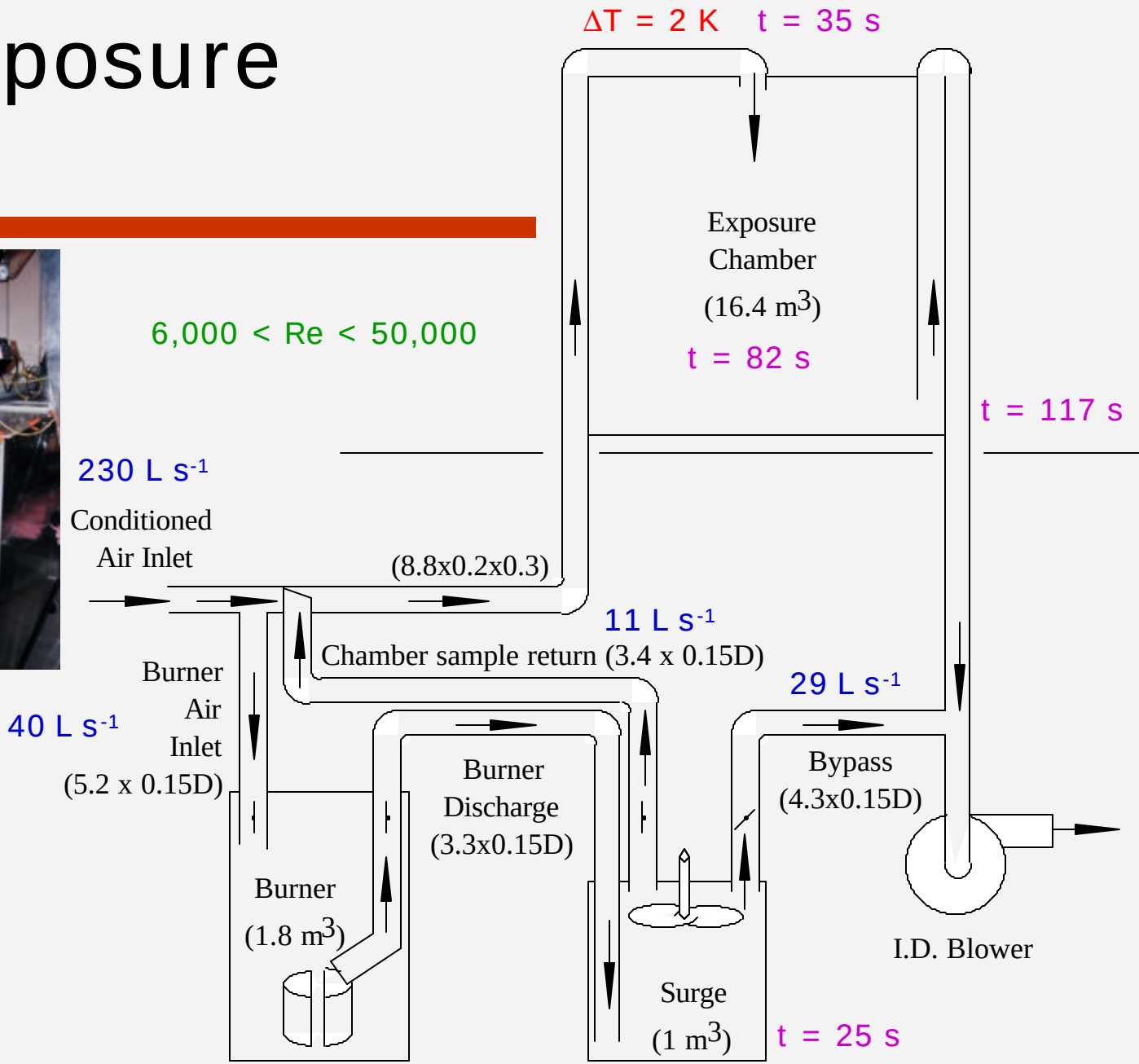
RSS Burner

- 14 rack storage magazine
- 280 shuttles/straws
- Manual preload
- Automatic feed and detect
- Programmable firing interval
- Continuous burner air flow (40 L s^{-1}, <20% of total to chamber), adjustable
- Radiant ignition (4.8 kW, flux = 65 kW m^{-2})
- Minimum design mass air-fuel = 1200
  - >2000 at 45 s
  - >6000 at 140 s firing interval

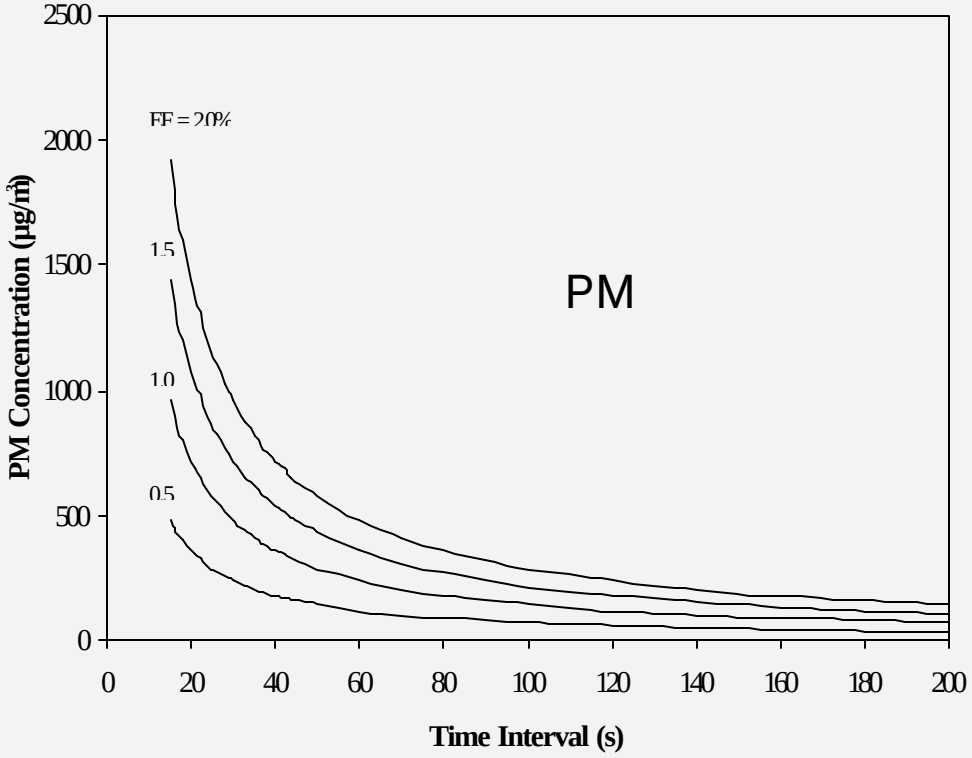


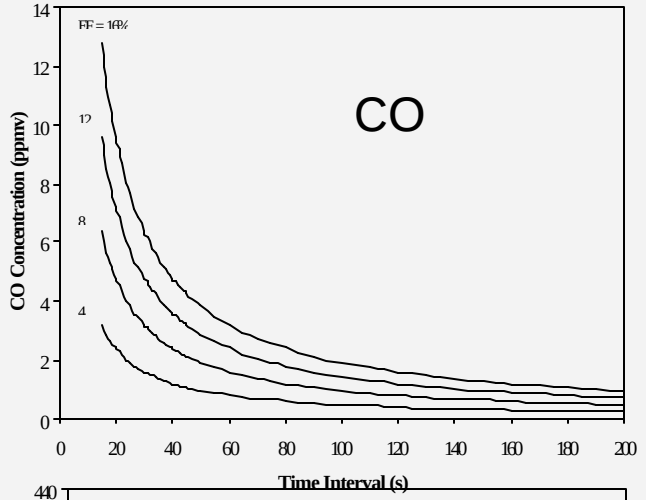
RSS Exposure System

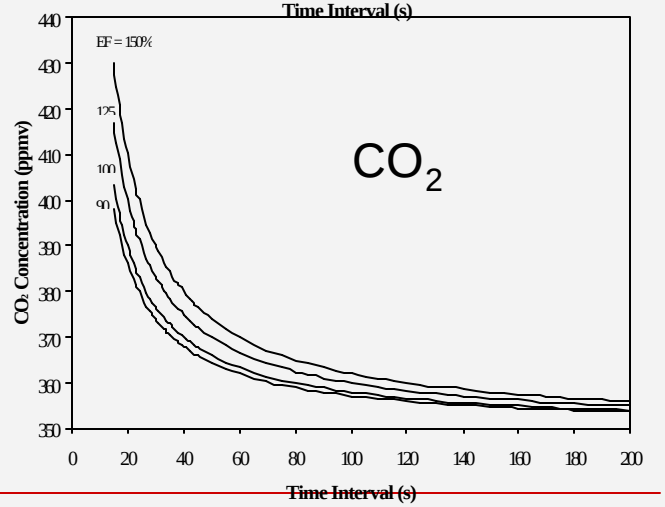




Chamber PM, CO, CO_2 Concentrations





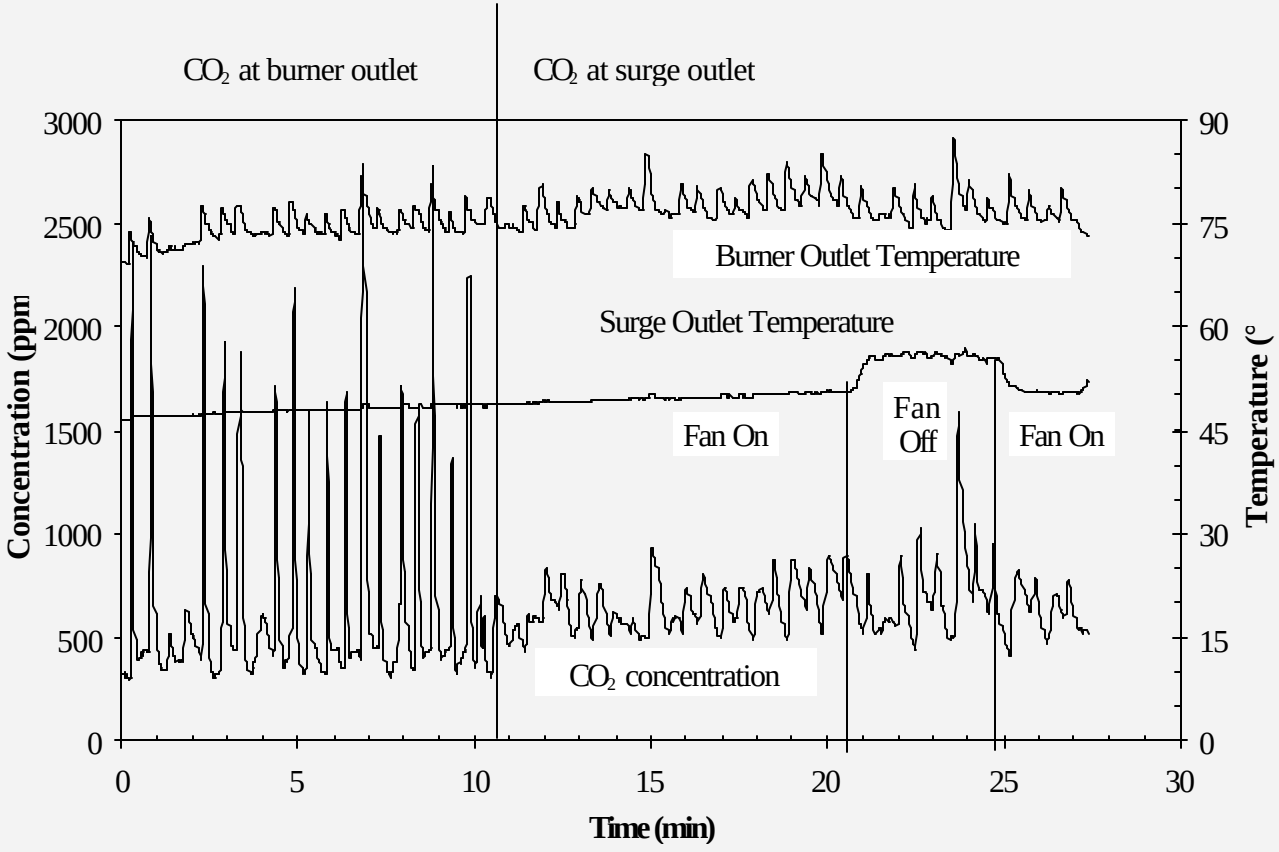


Results from Exposure Tests

	Low Concentration	High Concentration	Serial Day Exposure*
Straw Firing Interval (s)	140	45	140
Target PM Concentration (μg m^{-3})	200	600	200
Mean PM Concentration (μg m^{-3})	188	508	158
Number of tests	13	10	5
Range (μg m^{-3})	274	576	87
Minimum (μg m^{-3})	93	310	117
Maximum (μg m^{-3})	367	886	204
Standard deviation	75	202	32
Standard error	21	64	14
95% confidence interval (μg m^{-3})	± 45	± 144	± 40
Coefficient of Variation (%)	40	40	20

*exposures conducted on same subject on successive days.

Intermittency in burning



Transient Response

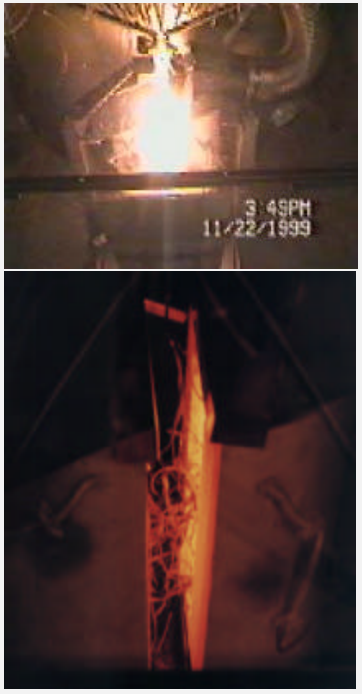
Surge Concentration (well mixed):

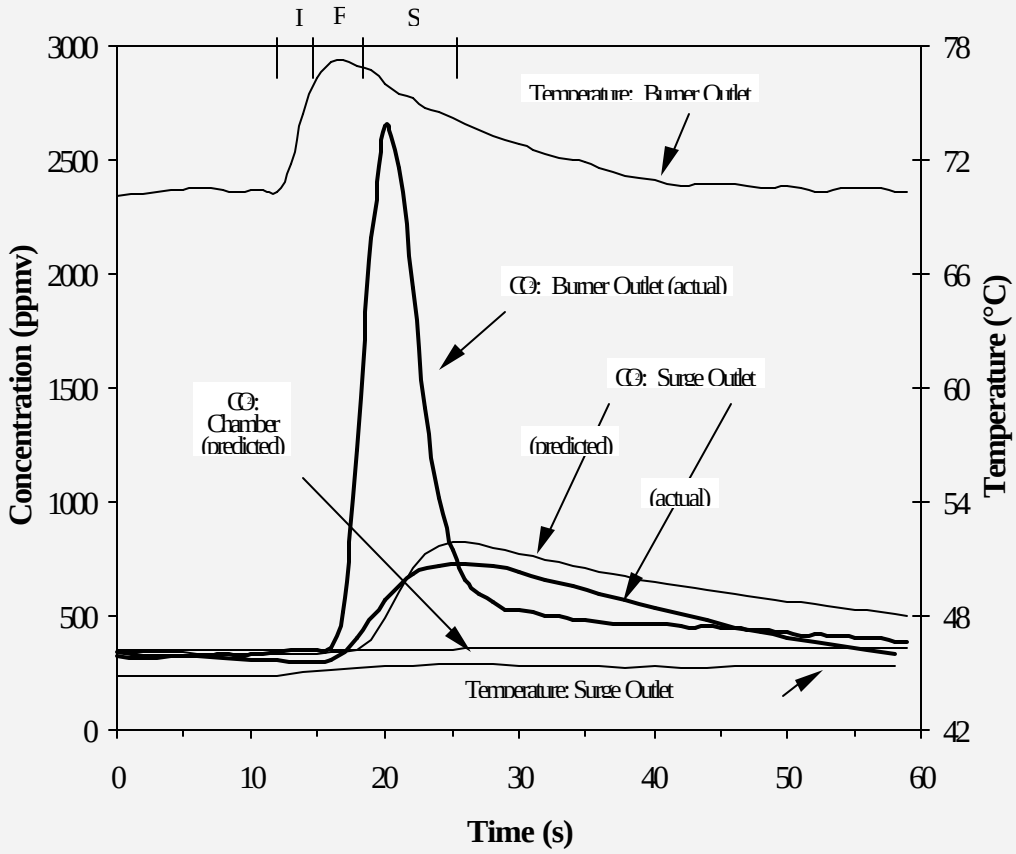
$$\frac{dC_s}{dt} = \frac{\dot{V}_{st}}{V_s}\frac{T_s}{T_{st}}\left[C_b - C_s\right]$$

Chamber Concentration (well mixed):

$$\frac{dC_c}{dt} = \frac{1}{V_c}\frac{T_c}{T_{st}}\left[\dot{V}_{st,s}(C_s - C_c) + \dot{V}_{st,o}(C_o - C_c)\right]$$

Induction, Flaming, Smoldering

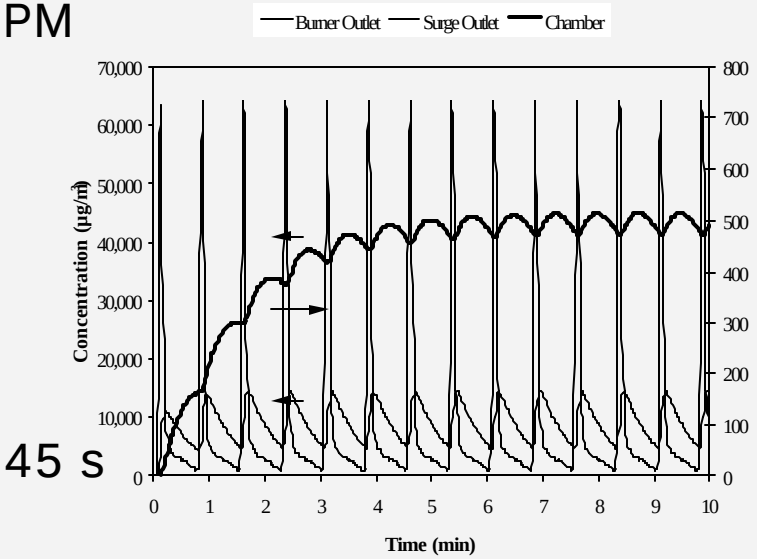




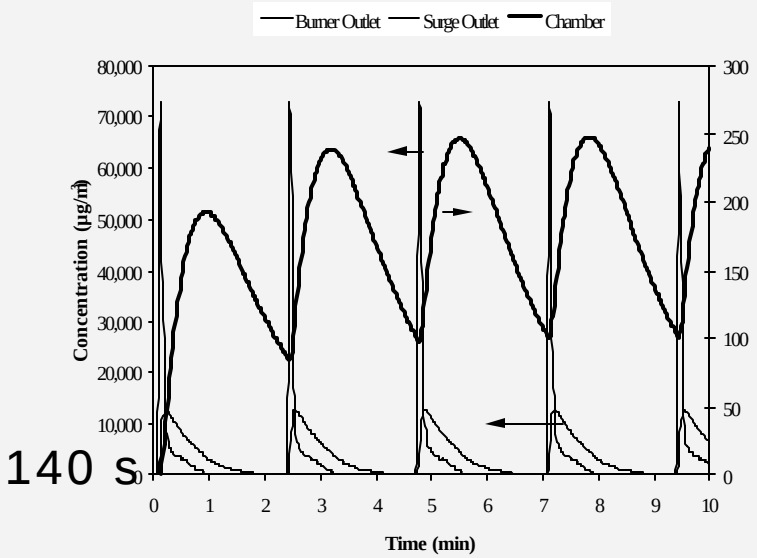
4 s sample lag on concentration, uncorrected

Predicted Concentrations

PM

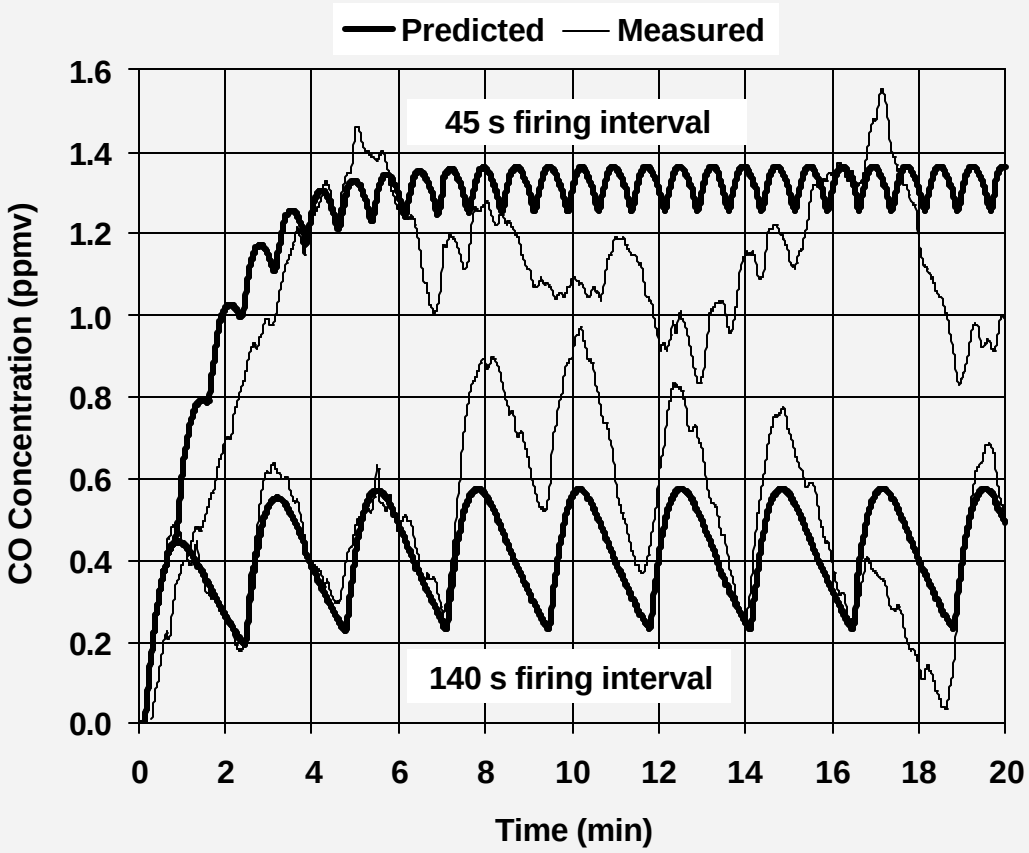


45 s

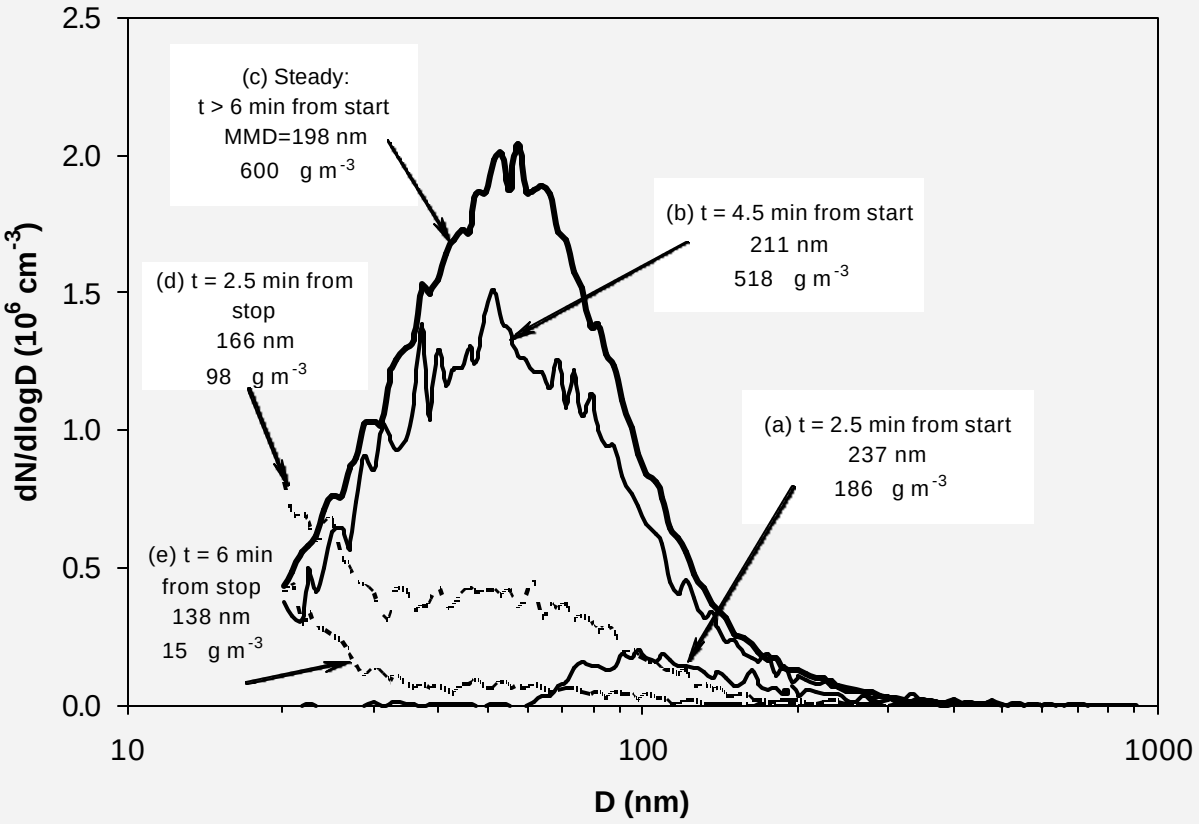


140 s

CO as surrogate
Predicted and Measured in Chamber

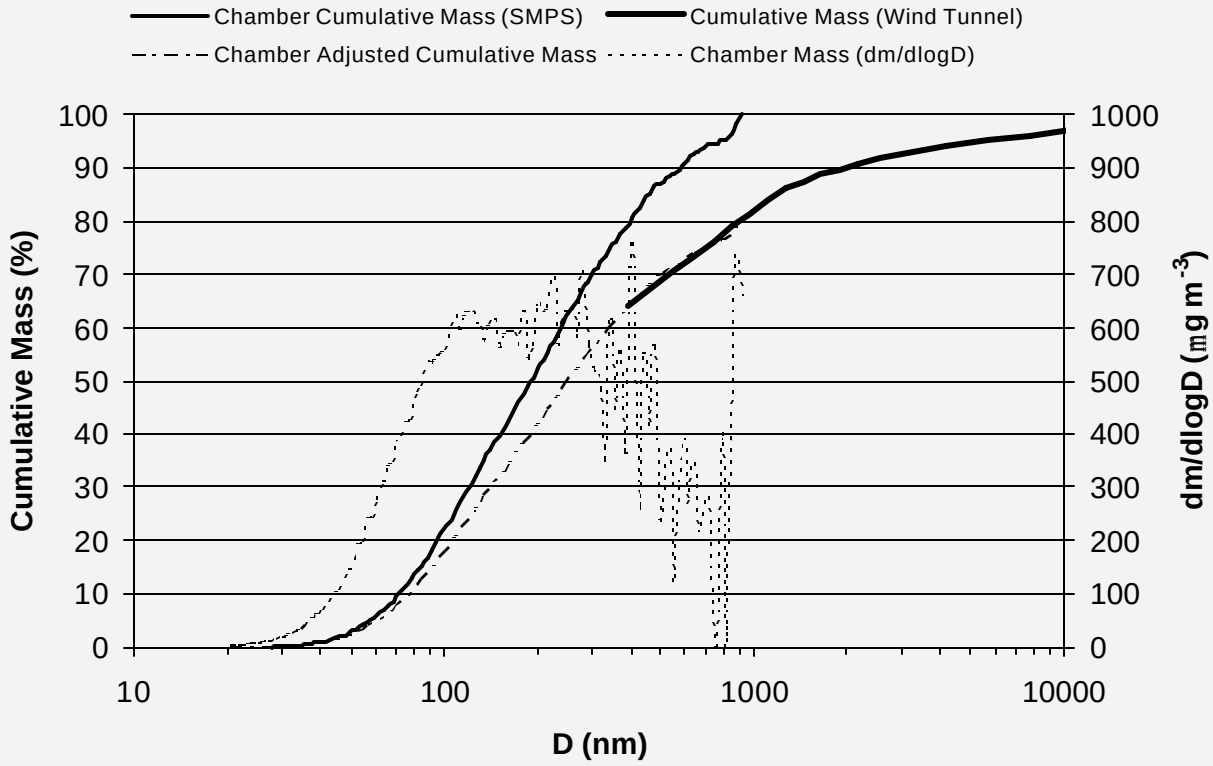


Particle Size Distribution by SMPS



Particle Mass Distribution

Aligned to wind tunnel at 80% mass by SMPS (< 930 µm)



PM Emission Factors
(% dry matter)

RSS Low Concentration (140 s firing interval)	1.89 ± 0.45%
RSS High Concentration (45 s firing interval)	1.65 ± 0.47%
RSS Serial Day Exposures (45 s firing interval)	1.59 ± 0.40%
RSS Aggregated Exposures	1.75 ± 0.25%
Mean Wind Tunnel, all rice straw	0.35 ± 0.10%
Wind Tunnel, similar rice straw	0.65 ± 0.22%
Field Measurements	0.1% to 2.2%
AP-42 (Darley)	0.4%
Predicted from K concentration in straw	0.54%

RSS System Performance

- Target concentrations achieved
- Excellent repeatability
- Similar particle size distributions
- Particle emission factors higher than previously measured in wind tunnel
  - Ignition failures (<10%)
  - Induction period prior to flaming
  - Fire configuration (wind tunnel strictly wind-opposed/backing)
  - Experimental uncertainty
  - Chemical characterization needed to assess implications for study

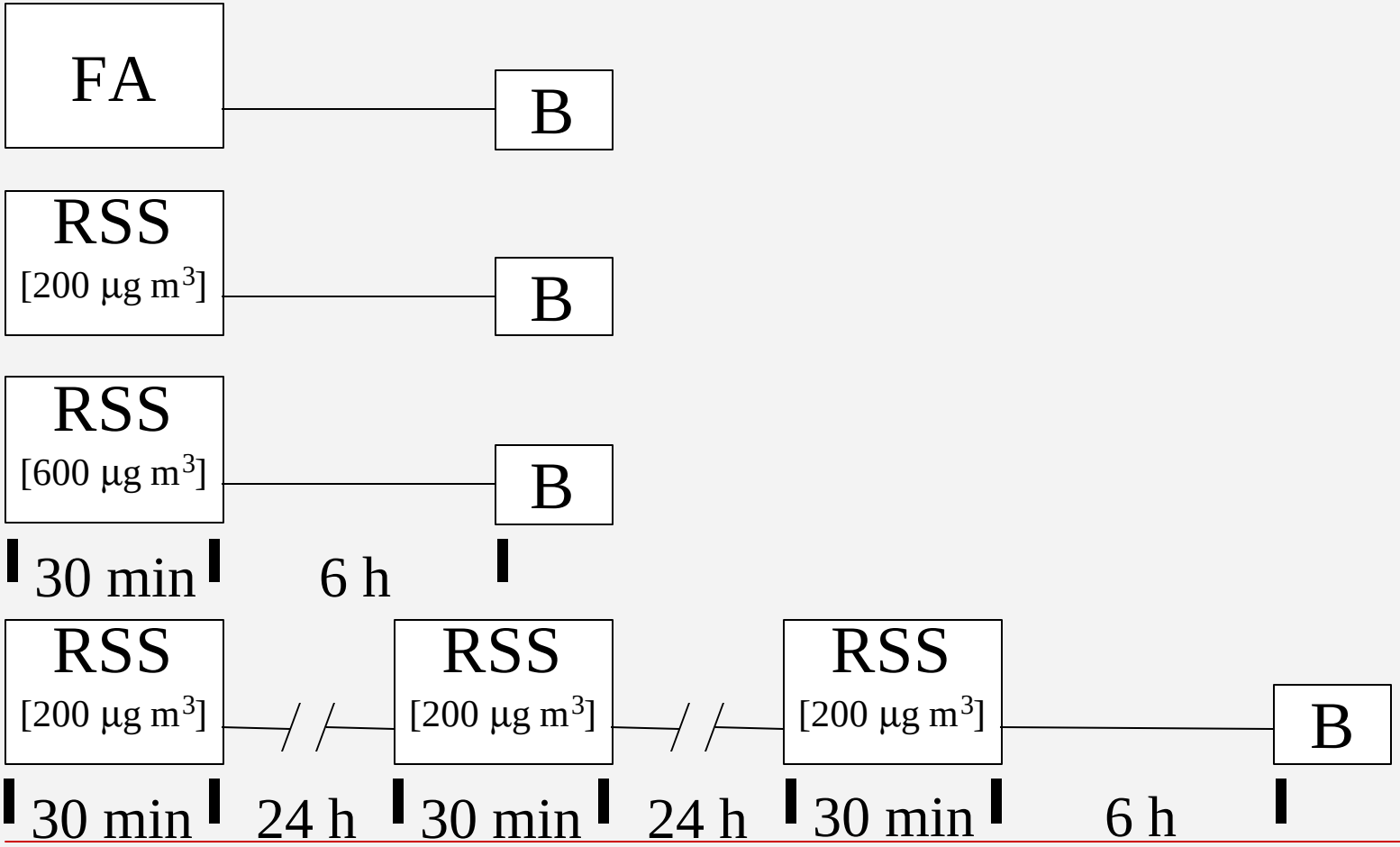
Method; Subjects

- n = 15 per group
- Healthy
  - Females = 5
  - Age (mean ± SD) = 30.6 ± 7.8 yr
- Asthma: PC_{20} < 10 mg ml methacholine.
  - Females = 13
  - Age (mean ± SD) = 31.2 ± 7.8 yr.
- Allergic-rhinitis: positive allergy skin test, symptoms.
  - Females = 9
  - Age (mean ± SD) = 31.7 ± 9.5 yr

Method; Procedures

- Exposure:
  - 30 min, seated at rest, nose clips.
  - Filtered air.
  - RSS; 200 μg m^3.
  - RSS; 600 μg m^3.
  - RSS; 3-days x 200 μg m^3.

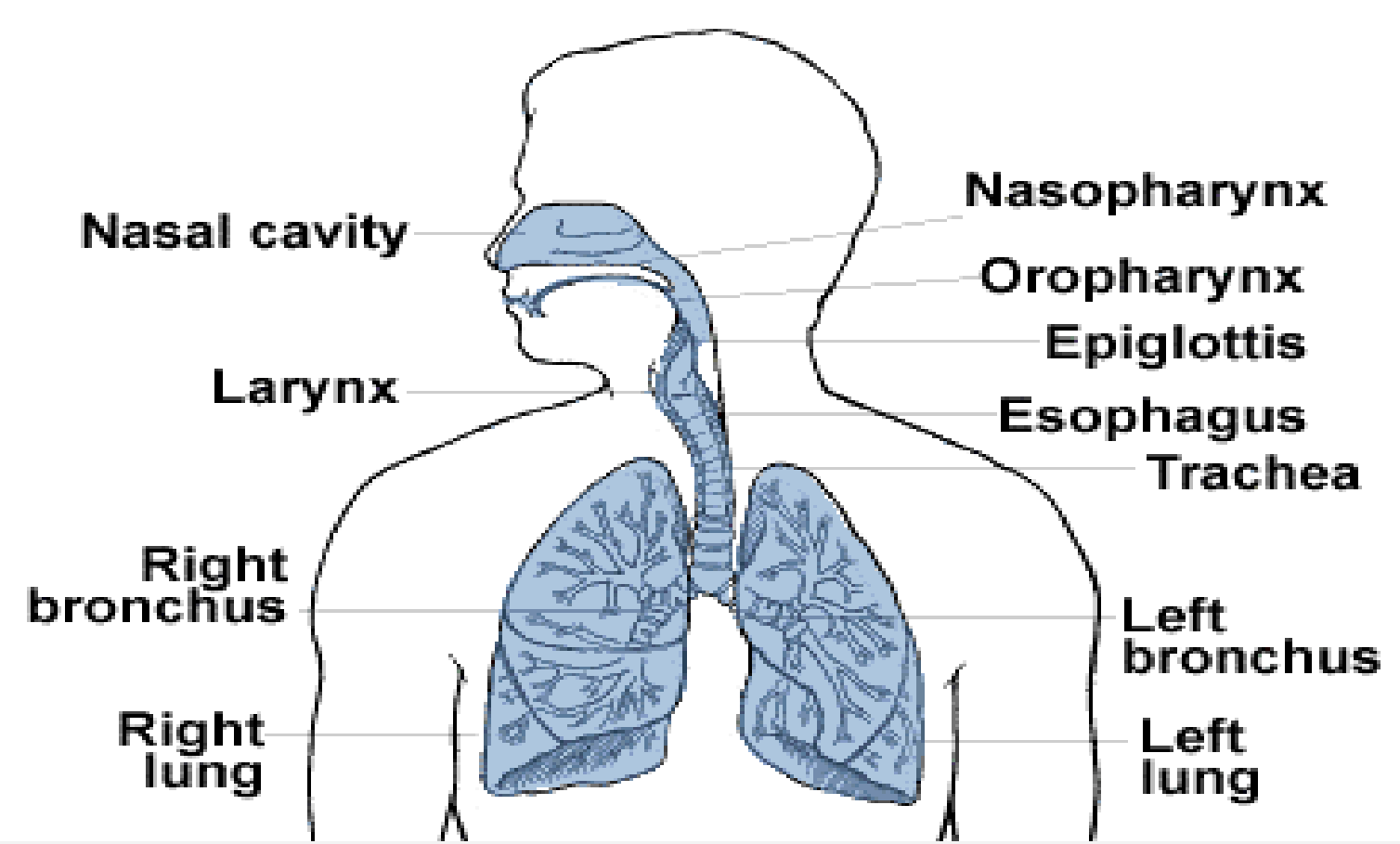
Method; Design



Method; Procedures

- Bronchoscopy:
  - 6 h post-exposure.
  - Bronchoalveolar lavage (BAL; 2 x 50 mL).
  - Bronchial fraction (Bfx; first 15 mL).

Method; Bronchoscopy



Method; Procedures

- Spirometry: Pre- and post-exposure.
- Symptoms: Pre- and post-exposure.

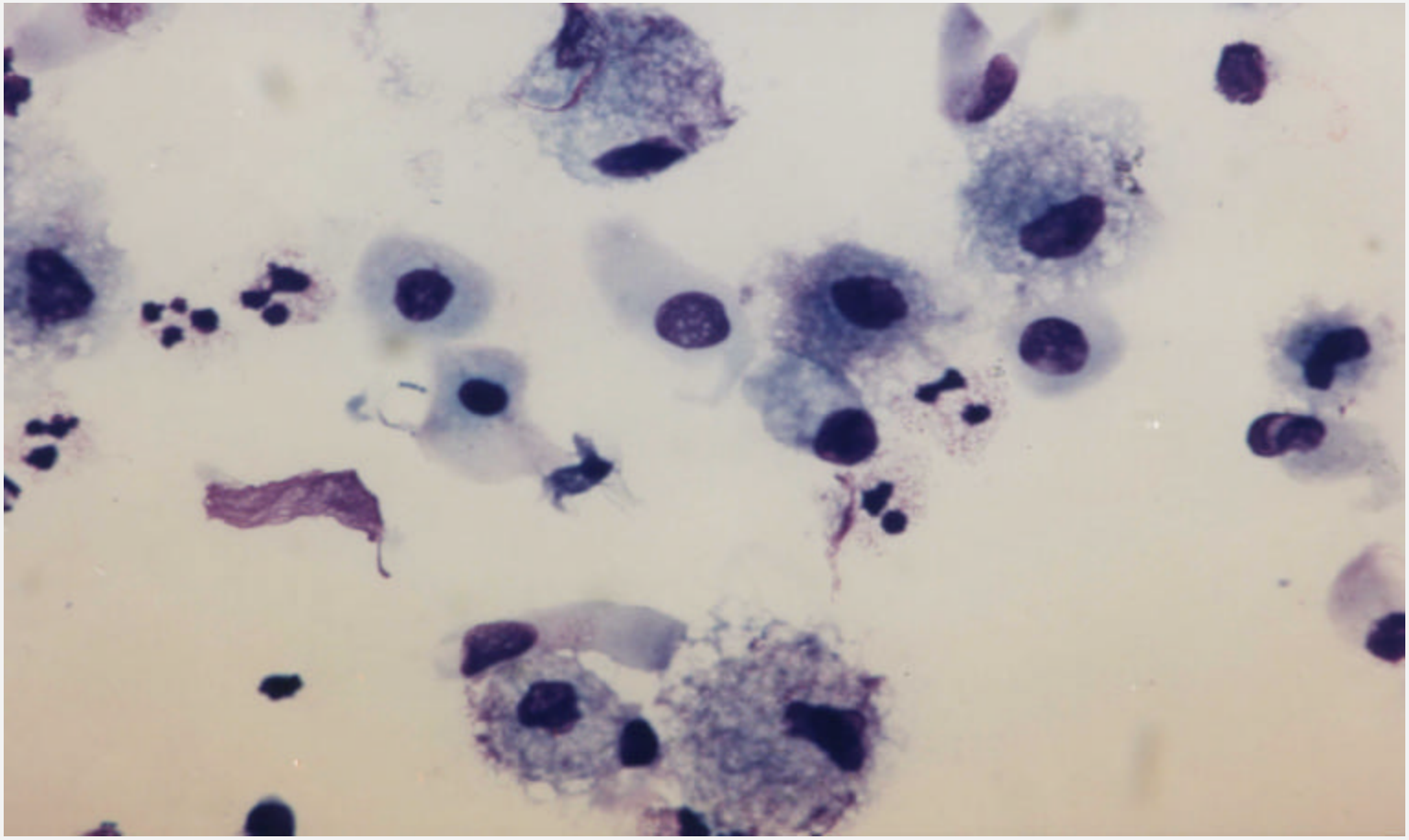
Method: Airway Grading

- Scale:
  - 0 = Normal
  - 1 = Mildly inflamed
  - 2 = Moderately inflamed
  - 3 = Severely inflamed

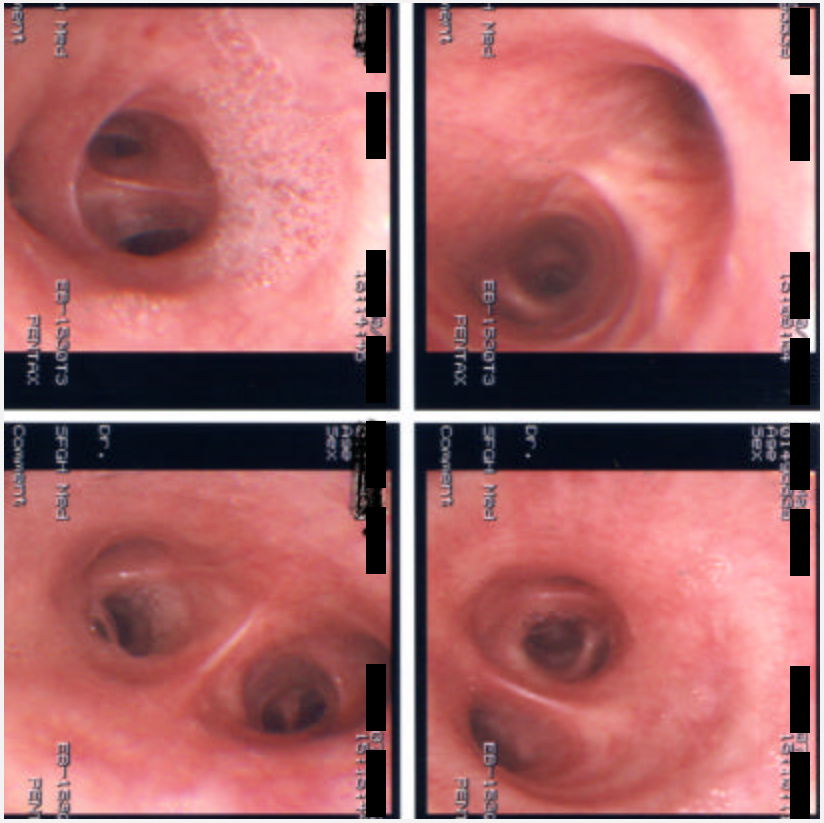
Method; Airway Inflammation

- Cells:
  - Macrophages (particle phagocytosis)
  - Neutrophils (inflammation)
  - Epithelial cells (initial contact; particle uptake)
- Proteins:
  - TNF-α (pro-inflammatory; early response)
  - IL-8 (neutrophil chemo-attractant)
  - MCP-1 (macrophage chemo-attractant)

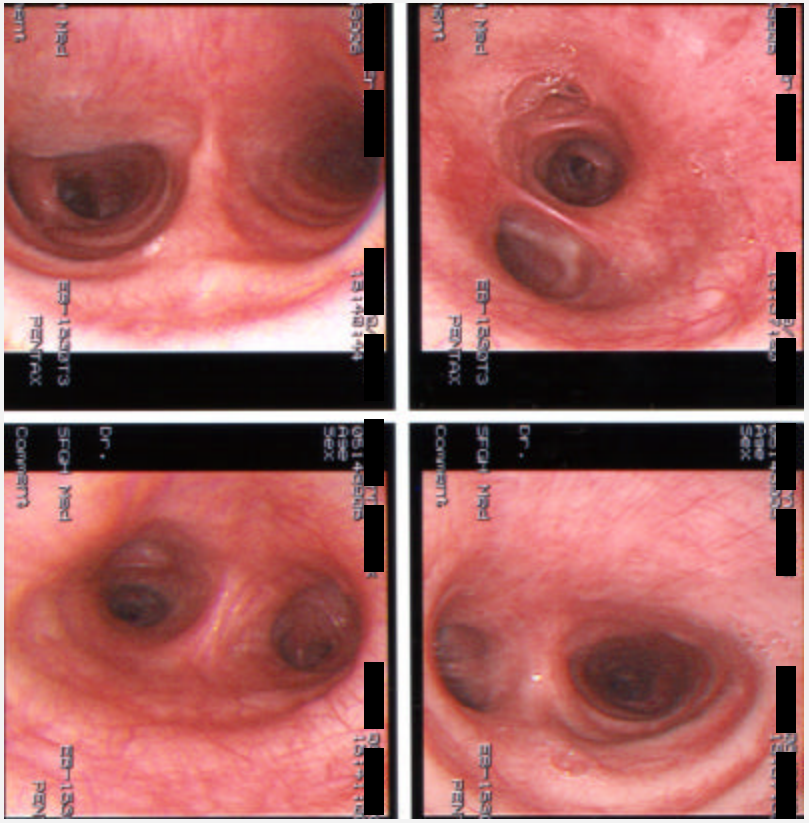
Method; Airway Cells



Results: Airway Grading

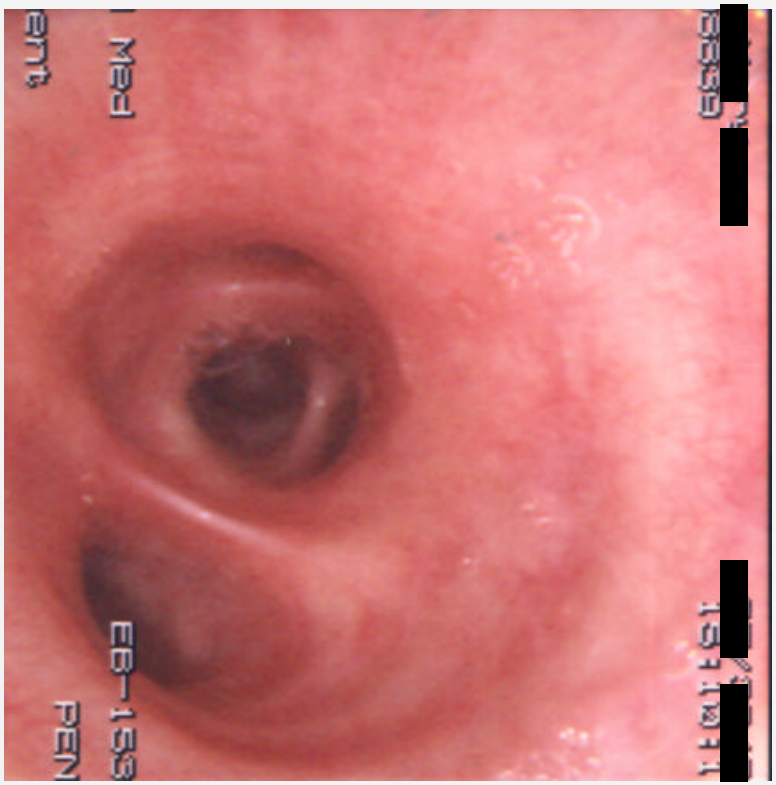


FA (0)

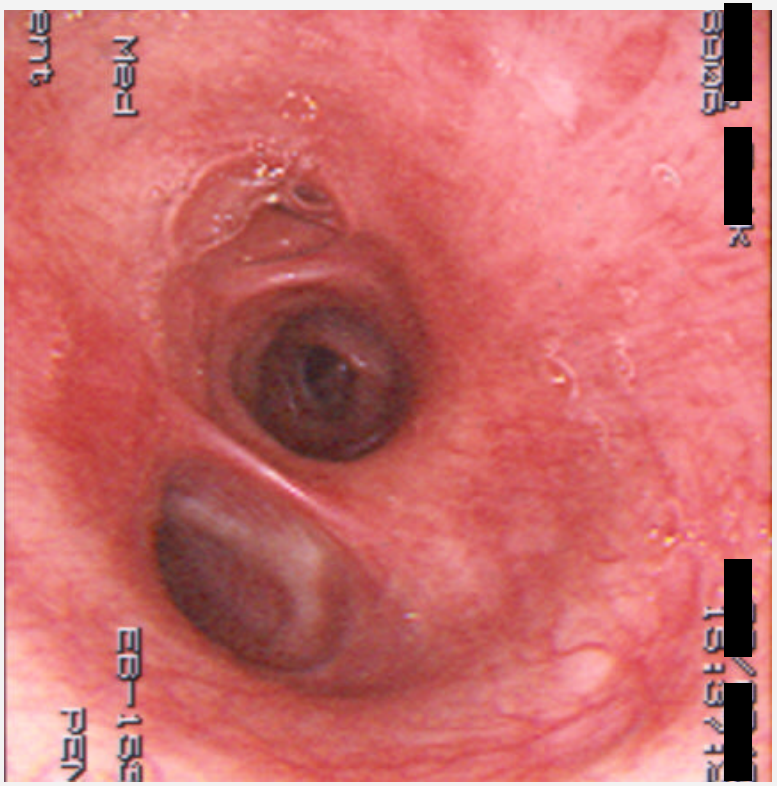


200 x 3 (2)

Results: Airway Grading



FA (0)

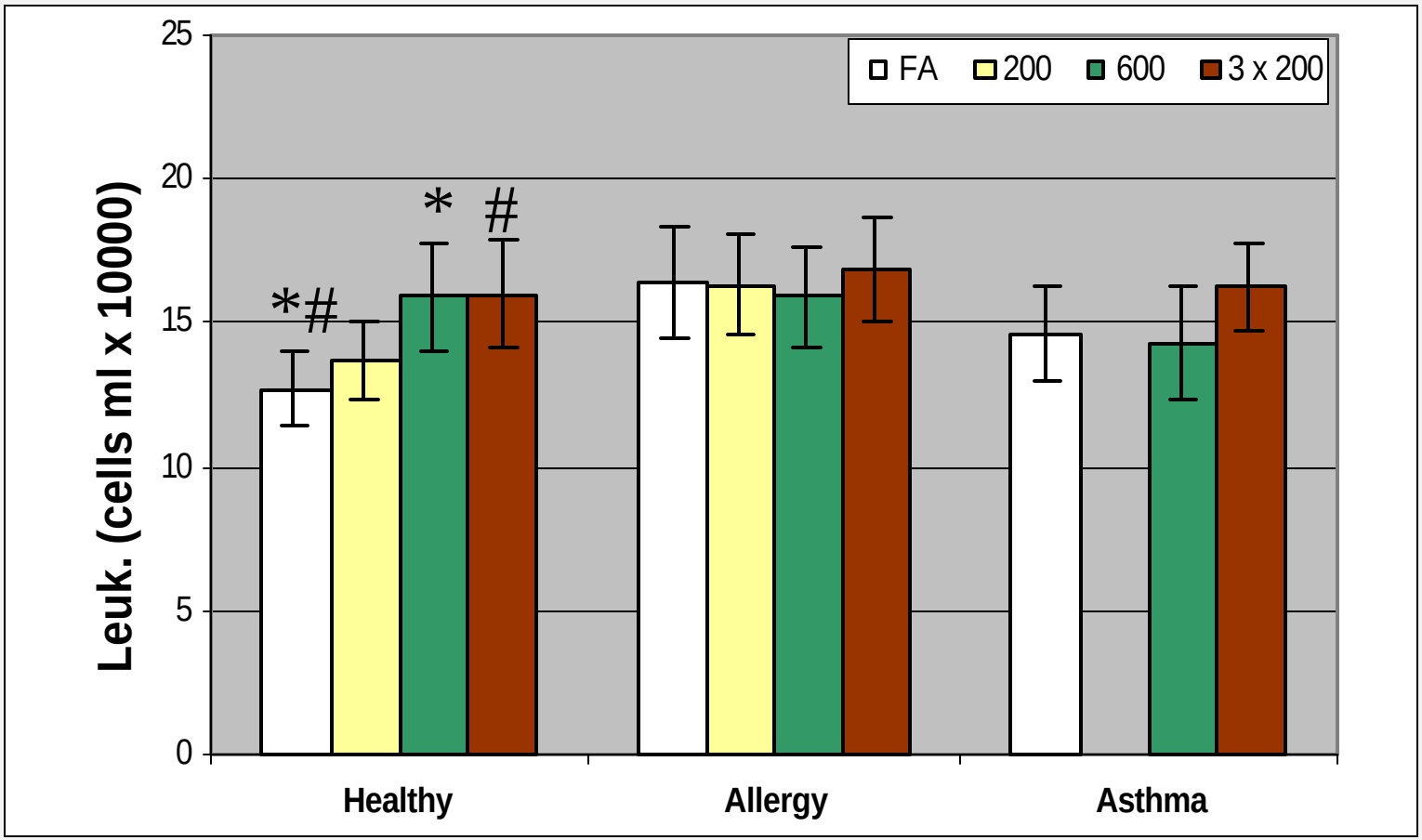


3 x 200 (2)

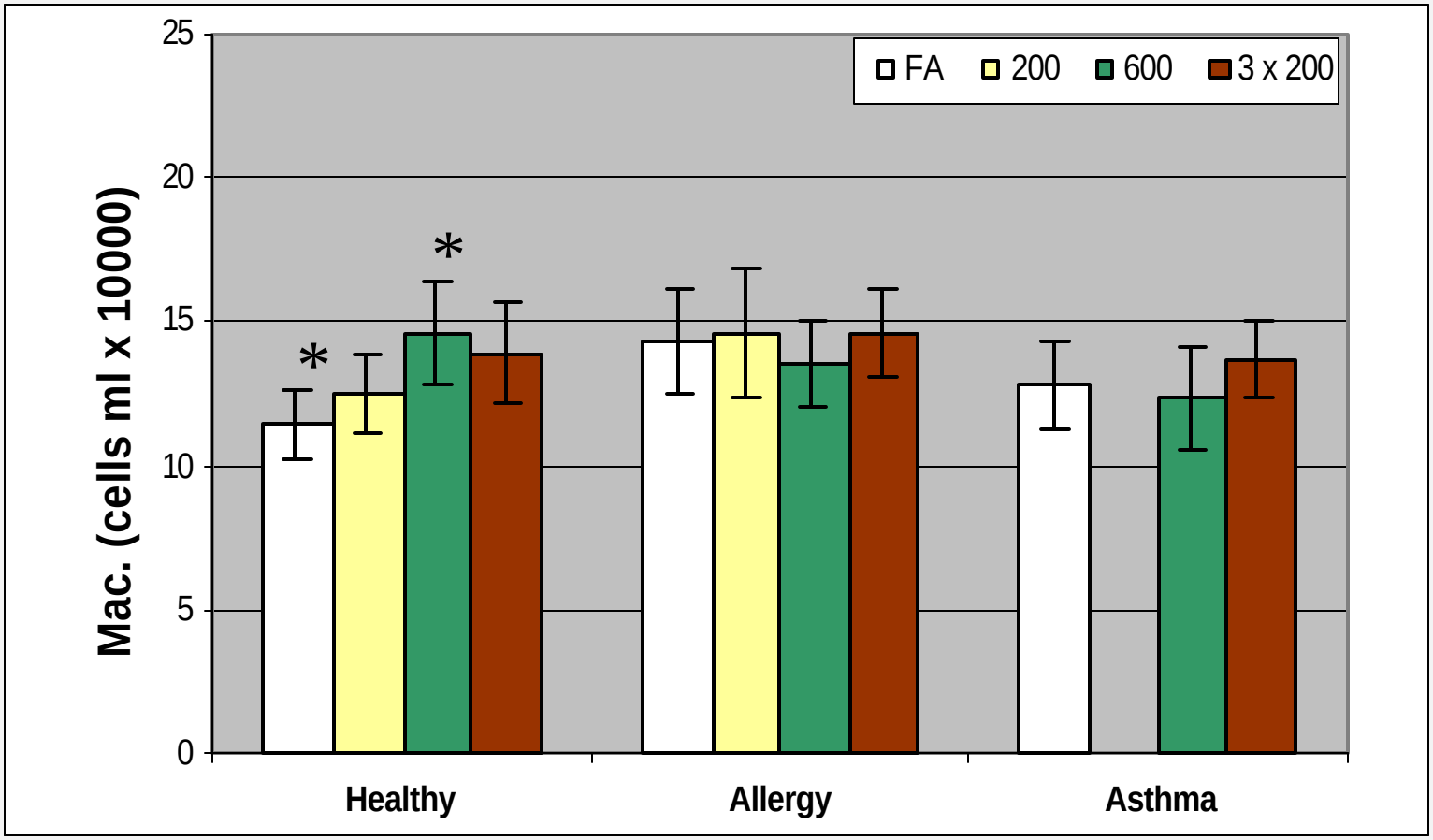
Results: Airway Grading

- Healthy
  - Increased; RSS-600 vs. FA, RSS-3x200 vs. FA
- Asthma
  - No RSS-induced changes (higher baseline)
- Allergic-Rhinitis
  - Increased; RSS-600 vs. FA

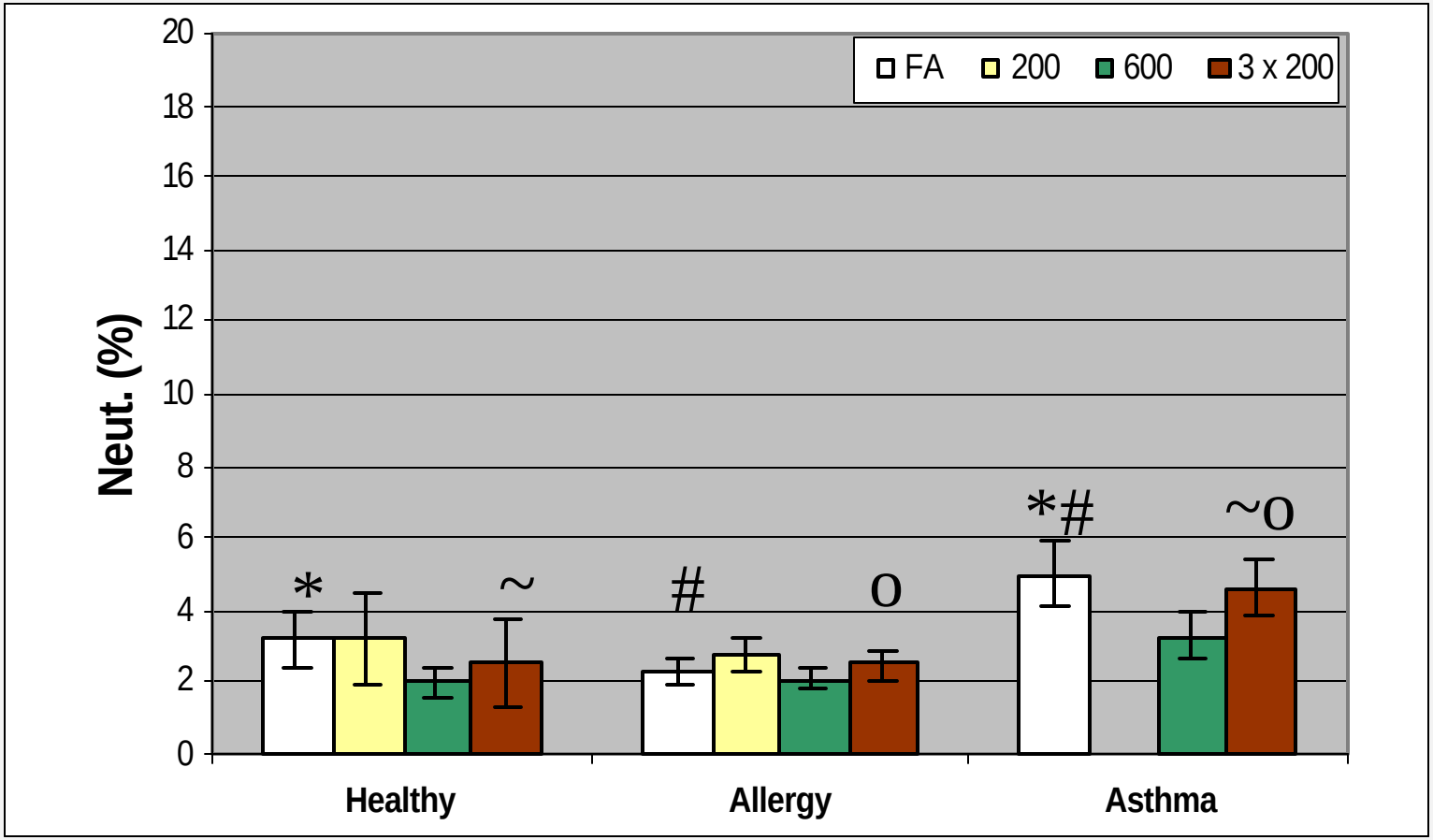
Results; Total Leukocytes (Bfx)



Results; Macrophages (Bfx)



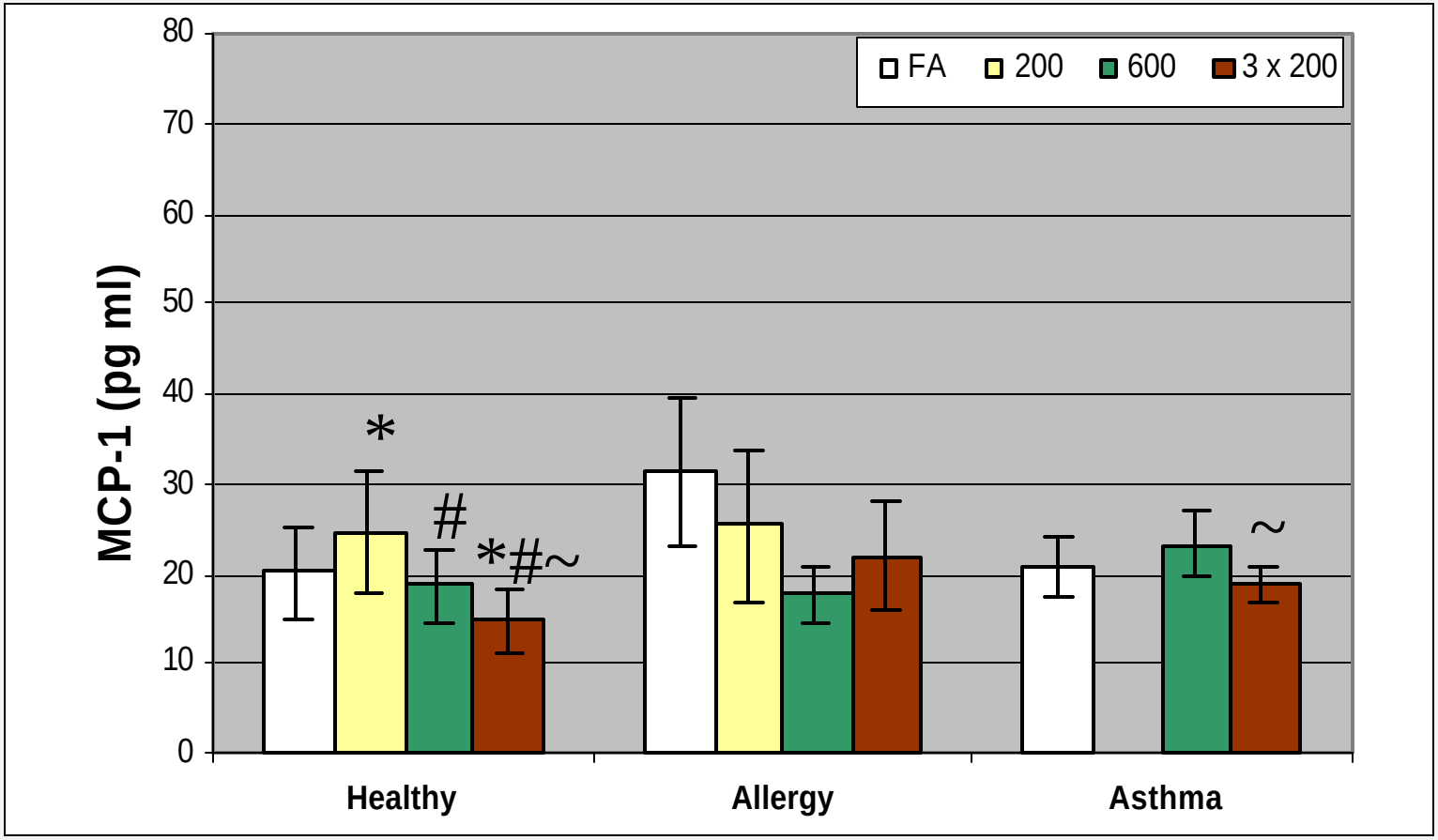
Results; Neutrophils (BAL)



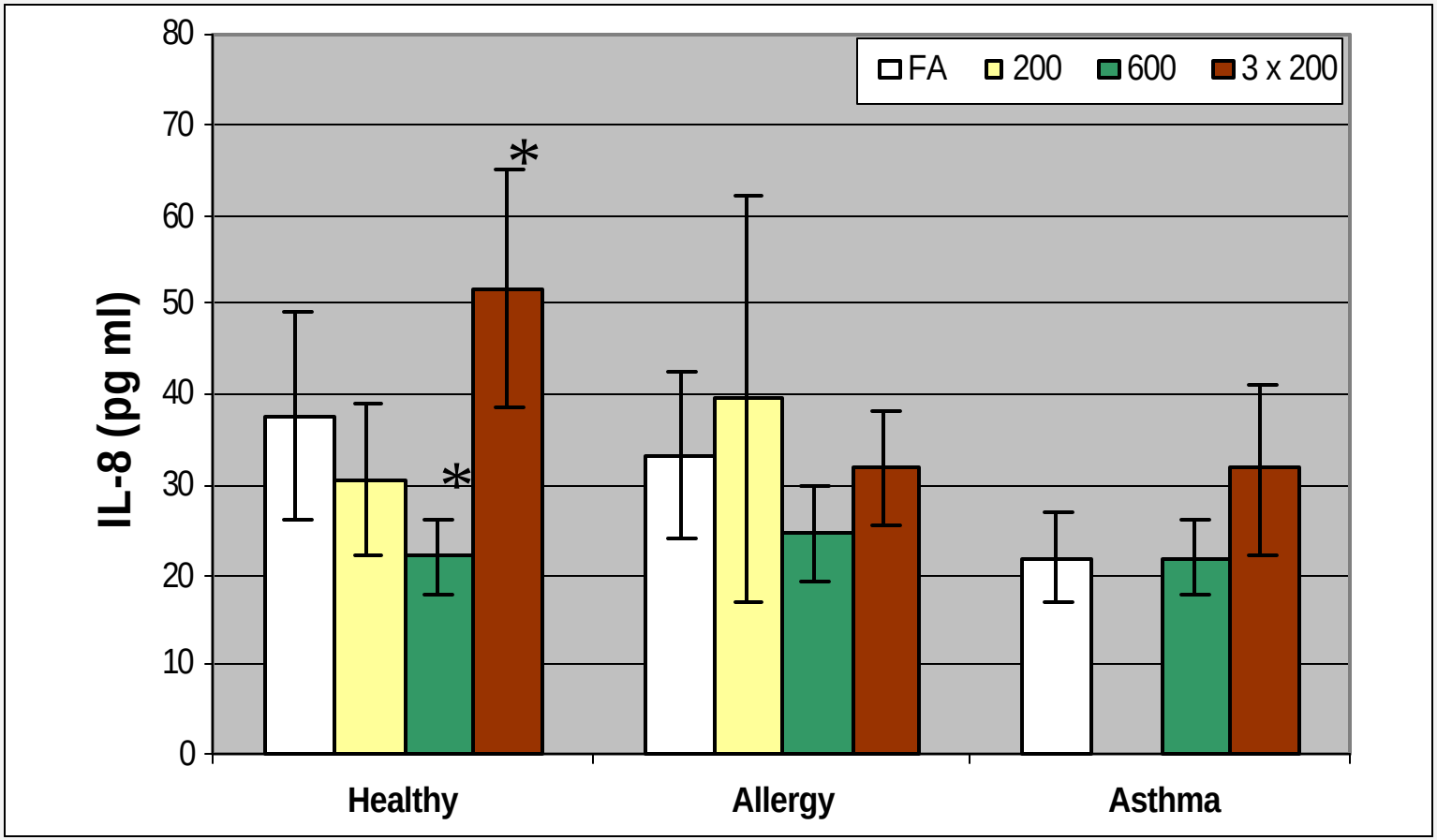
Results; Cells

- Healthy:
  - Increased total leukocytes
  - Increased macrophages
- Asthma:
  - Increased neutrophils
- Allergic-Rhinitis:
  - Decreased epithelial cells (airway injury)

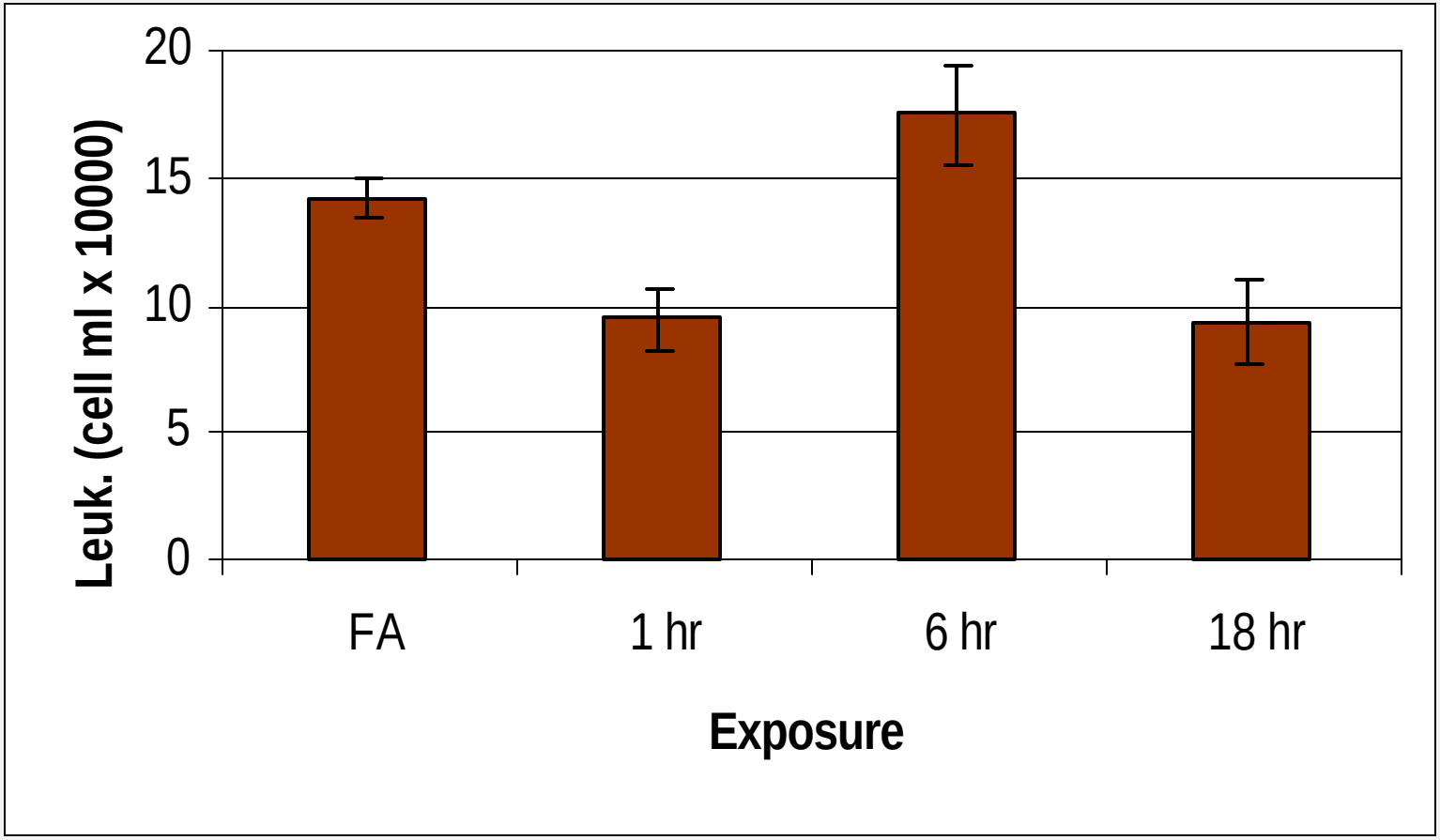
Results; MCP-1 (BAL)



Results; IL-8 (Bfx)



Results; Total Leukocytes (BAL); 1, 6, 18 h (Healthy; RSS-600)



Results

- No changes in RSS-200 $\mu g\ m^3$
- No meaningful changes in pulmonary function
- No changes in subject symptoms

Discussion

- The results of this project indicate that RSS is capable of inducing changes in airway cell distribution in healthy individuals, and in individuals with asthma, or allergic rhinitis.
- The specific RSS-induced changes in cells and proteins were different between the three subject groups.
- Asthma and allergic-rhinitis is associated with elevated inflammatory cells (leukocytes) at baseline. This could actually negate measurement of some RSS-induced inflammation.

Discussion

- The RSS-induced inflammation was present at low exposure doses compared to what could be expected in environmental situations, and compared to other controlled human exposure experiments:
  - 30 min.
  - Rest; no exercise.
  - Controlled human exposures:
    - Ozone (O_3); 0.2 ppm for 4 h x 4 day with exercise.
    - Nitrogen-dioxide (NO_2); 0.4 ppm for 4 h x 3 day with exercise.

Conclusions

- Inhaled RSS is not innocuous; induces airway inflammation.
- Inflammation occurs in the absence of changes in pulmonary function or symptoms (individuals may not remove themselves from the exposure).
- These results could be generalized to other forms of vegetative matter smoke exposure occurring world-wide (forest fires, residential wood smoke).

Future Research

- Delineate the toxic component(s) of smoke from vegetative matter.
- Particle vs. gas phase; essential for specific measurement and regulation.
- Determine threshold concentrations and doses for exposure regulation.

Future Research

- Effects on other susceptible populations, including individuals with cardiopulmonary disease.
- Other fuels: The UCD smoke generation system could be used to generate smoke from various vegetative matter, including other field residues, agricultural prunings, forest waste/biomass, and residential wood burning fuels.

Acknowledgements

UCSF

Isabelle Schmidlin

Allyson Witten

Peter Girling

Emilio Abritti

David Morris

Robert Jasmer

Mehrdad Arjomandi

John Balmes

UC Davis

Bryan Jenkins

Robert Williams

James Mehlschau

UC Irvine

Michael Kleinman

Diane Meacher

Funding

CARB