

In utero cigarette smoke exposure impairs somatic and lung growth in BALB/c mice.

Alexander N. Larcombe¹, Rachel E. Foong¹, Luke J. Berry¹, Graeme R. Zosky¹ and Peter D. Sly^{1,2}.

¹Division of Clinical Sciences, Telethon Institute for Child Health Research & Centre for Child Health Research, University of Western Australia, Perth, Australia.

²Queensland Children's Medical Research Institute, University of Queensland, Brisbane, Queensland, Australia

Corresponding author: Dr Alexander Larcombe
Division of Clinical Sciences
Telethon Institute for Child Health Research
PO Box 855
West Perth, Western Australia 6872
Ph: +618 9489 7819
Fax: +618 9489 7706
Email: alexanderl@ichr.uwa.edu.au

Abstract

The aim of this study was to assess whether *in utero* tobacco smoke exposure alone impacts early-life lung growth and development.

Pregnant BALB/c mice were exposed to cigarette smoke from 6 cigarettes per day, or air, from day 8 to 20 of gestation. At two weeks of age, pups were weighed and had their lung volumes and lung mechanics measured

Pups born from mothers exposed to cigarette smoke (CS, n = 17) were significantly lighter (6.76 ± 0.76 g vs. 7.72 ± 0.68 g) and had lower lung volumes (0.123 ± 0.02 mL vs. 0.149 ± 0.02 mL) than control (Air, n = 20) pups. Respiratory mechanics were adversely impacted by CS exposure. CS pups had higher baseline airway resistance (R_{aw}), tissue damping (G) and tissue elastance (H). These differences were largely due to lower lung volumes. Both G and H were increased excessively in CS pups at high transrespiratory pressures, while other parameters were not affected. There were no histological differences between groups.

in utero tobacco smoke exposure significantly impacts growth and development in BALB/c mice. These impacts may partially explain the susceptibility of infants born to smoking mothers to early respiratory disease and chronic respiratory disease as adults.

Keywords – cigarette smoke, *in utero*, lung function, mouse

Introduction

There are a plethora of epidemiological studies that link *in utero* and/or early life tobacco smoke exposure to altered lung function, wheeze, bronchitis and increased prevalence and severity of asthma in children [1-10]. Children born to smoking mothers show deficits in measured indicators of lung function, such as forced expiratory volume in one second, airflow at functional residual capacity and mean mid expiratory flow [3, 11]. There is considerable difficulty, however, in separating the effects of pre- and postnatal cigarette smoke exposure on lung function, as mothers who smoke during pregnancy rarely give up after the baby is born [12]. Further, in human studies, it is very difficult to separate the effects of cigarette smoke exposure from the effects of other factors which may alter lung function, such as respiratory viral, aeroallergen or pollutant exposure. Thus, it is not easy to evaluate the true impacts of *in utero* cigarette smoke exposure on developing lungs in humans [13], making the use of animal models of cigarette smoke exposure particularly relevant. Unfortunately, there is a paucity of data exploring the effects of *in utero* mainstream cigarette smoke exposure on early life lung function using animal models. A number of mouse studies have considered the effects of cigarette smoke exposure on allergic airways disease [14, 15], however these have generally investigated adult mice and/or use inappropriate measures of lung function such as “enhanced pause” [9, 14, 15]. Previous studies in rats have shown that *in utero* and postnatal exposure to sidestream cigarette smoke results in lungs which are less compliant and more reactive to methacholine as measured *in vitro* [16]. Postnatal or *in utero* exposure alone did not change lung function or airway reactivity to methacholine [17]. These studies did not measure early-life lung function or lung volume, but were restricted to investigating the effects of *in utero* cigarette smoke exposure on the lungs of adult offspring *in vitro*.

This study was designed to test the hypothesis that *in utero* cigarette exposure alone (i.e.

without postnatal cigarette smoke exposure, exposure to allergen or other confounders) results in impaired lung function in two-week old mice.

Materials and Methods

Animals

BALB/c dams (Animal Resource Centre; Murdoch, Western Australia) purchased at E5 were housed at the Telethon Institute for Child Health Research with a 12-h:12-h light / dark cycle and provided with food and water *ad libitum*. All experiments were conducted with the approval of the Institutional Animal Ethics Committee and conformed to the guidelines of the National Health and Medical Research Council of Australia.

Cigarette Smoke Exposure

Dams were placed in a custom made exposure chamber, (total volume 9.2L) attached to a commercially available cigarette smoking machine (*inExpose*, SCIREQ®, Montreal, Canada). Four dams were whole-body exposed to mainstream cigarette smoke generated from 3 Winfield Red cigarettes (≤ 16 mg of tar, ≤ 1.2 mg of nicotine and ≤ 15 mg of CO, Philip Morris, Melbourne, Australia) twice per day from E8 to E20 of gestation. Cigarettes were puffed using the ISO standard 35mL puff, once per minute such that each cigarette lasted ~8 minutes. Five minutes were left between cigarettes for air to flush through the chamber. Throughout exposure, medical air flowed through the system at 3L min^{-1} to ensure oxygen levels remained adequate. Four control dams received only medical air. Dams tolerated the exposure regime well and none died during experiments. CS dams produced a total of 17 pups, whilst Air dams produced a total of 20 pups.

Urine Cotinine

Urine cotinine levels in dams were measured after the last exposure on day 2, 4, 6, 8, 10, 12 and 13 (24 hours after the last exposure) by ELISA (Calbiotech, Spring Valley, USA). Urine from a minimum of 6 mice was tested per day.

Animal Preparation

At two weeks of age, pups were anesthetized with an intraperitoneal injection of a solution containing 20 mg/mL of ketamine (Troy Laboratories, NSW, Australia) and 1 mg/mL of xylazine (Troy Laboratories, NSW, Australia) at a dose of 0.1 mL/10 g body weight. Two-thirds of the dose was given initially to induce a surgical level of anesthesia. Once anesthetized, pups were tracheostomized with a 10-mm length of 21 gauge needle which was securely fixed *in situ* with surgical silk. The mouse was placed inside a whole body plethysmograph and connected to a small animal ventilator (Minivent, Harvard, March-Hugstetten, Germany). The remaining anaesthetic was given, and the mouse was ventilated at 400 breaths/min with a tidal volume of 8 mL/kg and 2 cmH₂O of positive-end expiratory pressure. This was sufficient to suppress spontaneous breathing efforts during measurements without the need for paralysis. Except when measurements were being made, the plethysmographic box was open to the atmosphere, and the mouse was ventilated with atmospheric air.

Thoracic Gas Volume

Thoracic gas volume (TGV) was measured plethysmographically as described previously [18]. Briefly, during a pause in ventilation, the box and airway opening were occluded, making the system completely airtight, and box (P_{box}) and tracheal (P_{trachea}) pressures measured using pressure transducers (Validyne MP45, Validyne Engineering, Northridge, CA, USA and model 8507C-2, Endevco, San Juan Capistrano, CA, USA respectively) for a

period of 6 seconds, during which time inspiratory breathing efforts were created by stimulating the intercostal muscles with electrical impulses ~ 20 V in amplitude and ~ 1 -2 ms in duration (model S44, Grass Instruments, Quincy, MA). During the 6 seconds of measurement, box thermal drift was negligible (Supplementary Figure 1). Six stimulations were made per mouse. Each stimulation was analysed separately and an average taken for each mouse, such that we report one TGV measurement per animal. TGV was calculated by applying Boyle's law to the relationship between P_{box} and P_{trachea} . Recordings were corrected for the thermal characteristics of the plethysmograph as previously described [18]. Briefly, P_{box} was corrected for deviations from the isothermal compression of the box gas by taking into account the isothermal elastic modulus of the box, atmospheric pressure and the volume of gas in the plethysmograph. With this correction, Boyle's law can be assumed during respiratory efforts, whereby the change in box volume is equal but opposite in sign to that in thoracic volume [18]. The frequency response / thermal characteristics of the plethysmograph were measured regularly during the experimental period, and did not change over the course of experimentation. During all TGV measurements, the plethysmography box was completely sealed. Daily confirmation that the box was airtight was achieved by applying a negative pressure to the system (Supplementary Figure 1).

Lung Mechanics

We measured respiratory system impedance (Z_{rs}) using a modification of the forced oscillation technique as previously described by our group [19]. Briefly, Z_{rs} was measured using a wave-tube system [20] adapted for use in small animals [19, 21]. During brief periods of apnea, oscillatory signals between 4 and 38 Hz (signal period 0.5 s) were generated by a loudspeaker and delivered via a 2 metre long wave-tube (internal diameter = 0.116 cm) to tracheostomised pups. Two transducers (model 8507C-2, Endevco, San Juan Capistrano, CA,

USA) were used to measure lateral pressure at either end of the wave-tube and Z_{rs} was estimated as the load impedance on the wave-tube. The constant phase model [22] was used to partition Z_{rs} into the airway compartment: airway resistance (R_{aw}) and inertance (I_{aw}) and the tissue compartment: tissue damping (G) and tissue elastance (H). I_{aw} values were negligible after correction for the inertance of the cannula and are not reported. Six measurements of baseline Z_{rs} were measured per mouse and averaged to achieve one value per animal. Z_{rs} was measured at baseline and also continuously during slow inflation (time = 20 s) from a P_{rs} of 0 to 20 cmH₂O. Lung inflation was achieved by evacuating the sealed plethysmograph with a regulated vacuum source. Hysteresivity (η) was calculated as G/H [22].

Histology

Lungs were fixed by intratracheal instillation of 2.5% glutaraldehyde at 10 cmH₂O [23]. The trachea was ligated with suture and the lungs removed *en bloc* and stored in 2.5% glutaraldehyde. Lungs were randomly oriented to ensure that sections were isotropic and uniformly random [24] and embedded in paraffin. Sections 5 μ m thick were taken at 500 μ m intervals from a random starting point, stained with haematoxylin-eosin and examined under light microscopy. Point counts were used to calculate parenchymal volume (V_p) and the volume of the alveolar septa (V_s). Surface area of the alveoli (S_a) was measured using a line intersection test grid [23].

Statistics

Analysis of mass was conducted using two-way ANOVA with sex and treatment as factors. Analysis of TGV was conducted using ANCOVA with mass as a covariate. Baseline lung function and the volume dependence of lung mechanics were compared using ANCOVA with

TGV as a covariate. Data were transformed using log or power transformations when required. Histology data were analysed by *t*-test. Statistical analyses were performed using SigmaStat (v3.50 SPSS Science, Chicago, IL, USA) and Stata (v10 Statacorp LP, College Station, TX, USA). Unless otherwise stated, data are shown as mean \pm SD.

Results

Urine Cotinine

Urine cotinine was relatively stable throughout pregnancy. There was no change in urine cotinine (average 5799 ± 2103 ng/mL) between days 2 through 12 ($p = 0.55$), however urine cotinine decreased 24 hours after the last cigarette exposure (982 ± 409 ng/mL). Cotinine was not detectable in the urine of control dams.

Effect of Sex

There was no significant interaction between treatment (i.e. *in utero* cigarette smoke exposure or air) and sex for any parameter investigated (all $p > 0.24$). As such, unless otherwise stated, all analyses were performed on combined male and female data.

Mass

Pups born to dams exposed to cigarette smoke during pregnancy (CS, $n = 17$) had lower masses (6.76 ± 0.76 g) than control (Air, $n = 20$) (7.72 ± 0.68 g) pups ($p < 0.001$). Litter sizes were not significantly different between treatments (*t*-test $p = 0.27$; average 3.75 ± 1.89 for CS pups and 5.00 ± 0.82 for Air pups).

TGV

TGV was measured on 20 Air and 17 CS pups. CS pups (0.123 ± 0.02 mL) had lower TGV

than Air pups (0.149 ± 0.02 mL) ($p < 0.001$), however, when mass was taken into account, there was no difference in the TGV ($p = 0.33$; Figure 1).

Baseline Lung Mechanics

Baseline lung mechanics were measured on 20 Air and 17 CS pups. There were significant effects of *in utero* cigarette smoke exposure on baseline lung mechanics, however for all parameters this difference was due to the smaller TGV of CS pups compared to Air pups (Figure 2). Baseline R_{aw} of CS pups (854.3 ± 121.3 hPa.s.L⁻¹) was significantly higher than that of Air pups (761.4 ± 93.0 hPa.s.L⁻¹; $p = 0.01$) but not after correcting for TGV ($p = 0.11$). Similarly, tissue damping (G) was significantly higher in CS pups (24910 ± 3461 hPa.L⁻¹) compared to Air pups (21991 ± 2413 hPa.L⁻¹) ($p < 0.01$) but not after correcting for TGV ($p = 0.26$). Likewise, baseline H of CS pups (90320 ± 15885 hPa.L⁻¹) was significantly greater than that of Air pups (78918 ± 9596 hPa.L⁻¹) ($p = 0.01$) but not after correcting for TGV ($p = 0.41$). η was not influenced by TGV ($p = 0.84$), and was not significantly different between CS pups (0.328 ± 0.01) and Air pups (0.293 ± 0.01).

Volume Dependence of Lung Mechanics

The volume dependence of lung mechanics was measured on 20 Air and 17 CS pups. The volume dependencies of R_{aw} , G, H and η were analysed at $P_{rs} = 20$ cm H₂O and at the P_{rs} at which TGV was equal to 50% of maximum TGV (TGV₅₀; Figure 3). All statistical analyses were conducted with TGV as a covariate. Raw of CS pups was not significantly different to that of control pups at either TGV₅₀ (CS: 636.70 ± 164.4 hPa.s.L⁻¹, Air: 557.80 ± 95.31 hPa.s.L⁻¹; $p = 0.078$; Figure 4) or at $P_{rs} = 20$ cm H₂O (CS: 157.39 ± 83.32 hPa.s.L⁻¹, Air: 179.75 ± 70.97 hPa.s.L⁻¹; $p = 0.822$).

Conversely, *in utero* cigarette smoke exposure had significant effects on both tissue damping and tissue elastance, even when differences in TGV were taken into account (Figure 4). The greatest effects of *in utero* cigarette smoke exposure was measured in G which was higher in CS compared to Air pups at both $P_{rs} = TGV_{50}$ (CS: $23267 \pm 3847 \text{ hPa.L}^{-1}$, Air: $20405 \pm 2506 \text{ hPa.L}^{-1}$; $p = 0.011$) and $P_{rs} = 20 \text{ cm H}_2\text{O}$ (CS: $61000 \pm 10253 \text{ hPa.L}^{-1}$, Air: $52525 \pm 7052 \text{ hPa.L}^{-1}$; $p = 0.018$). Tissue elastance was significantly influenced by *in utero* tobacco smoke exposure at $P_{rs} = 20 \text{ cm H}_2\text{O}$ (CS: $466193 \pm 66536 \text{ hPa.L}^{-1}$, Air $416928 \pm 63147 \text{ hPa.L}^{-1}$; $p = 0.017$) but not at $P_{rs} = TGV_{50}$ ($p = 0.096$).

There were no significant effects of *in utero* cigarette smoke on hysteresivity at either P_{rs} . At $P_{rs} = TGV_{50}$, η of CS pups (0.307 ± 0.051) was not different to that of Air pups (0.322 ± 0.034 ; $p = 0.627$). Similarly, at $P_{rs} = 20 \text{ cm H}_2\text{O}$, η of CS pups (0.131 ± 0.014) was not different to that of Air pups (0.128 ± 0.013 ; $p = 0.451$).

Histology

Histology was measured on a randomly selected sub-sample of 8 pups from each treatment. There were no differences between CS and Air pups for any histological measurement. V_p was not significantly different between Air ($140.4 \pm 37.0 \text{ mm}^3$) and CS ($121.8 \pm 15.02 \text{ mm}^3$) pups ($p = 0.386$). V_s was almost identical between Air ($52.3 \pm 7.4 \text{ mm}^3$) and CS ($52.5 \pm 5.9 \text{ mm}^3$) pups ($p = 0.953$) and S_a was similar between treatments ($6682.4 \pm 609.4 \text{ mm}^2$ for Air pups and $6091.3 \pm 1166.1 \text{ mm}^2$ for CS pups; $p = 0.404$).

Discussion

Pups born from mothers exposed to mainstream cigarette smoke during pregnancy were smaller and had lower lung volumes than control pups at 2 weeks of age. This impaired

development resulted in differences in lung mechanics; particularly when the lungs were inflated. This has important implications in that previous studies do not investigate the potential impacts of *in utero* cigarette smoke exposure on lung mechanics at high transrespiratory pressures. Differences in airway and parenchymal mechanics with the lungs at rest were explained by difference in lung size, as expressed by lung volume.

The effects of maternal smoking on intrauterine growth are well documented [2]. It has been known for some time [25] that maternal smoking adversely effects birth weight and length [8], and more recently this effect has been confirmed to be directly dose related [26]. In mouse pups, we found that *in utero* exposure to cigarette smoke resulted in pups that were almost 1g (~12% total body weight) lighter than Air pups at 2 weeks of age. Importantly, this was not a function of litter size, nor was it due to preterm delivery as there were no differences in litter size or gestational period between CS and Air dams. This agrees with the findings of human studies which suggest that the lower weights of babies born to smoking mothers are due to intrauterine growth impairment rather than premature delivery [8, 27, 28]. Babies born to smoking mothers have been estimated to be 5% (~150 and 300g) lighter per pack of cigarettes smoked per day by the mother [28, 29], and birth weight is significantly lower in babies born to mothers who self-report smoking as little as one cigarette per day [30]. Maternal smoking can alter fetal growth in a number of ways, including transient reductions in maternal uterine blood flow and fetal hypoxia [32, 33]. Discussion of these is beyond the scope of this investigation, however it is also known that impaired intrauterine growth has a lasting effect on subsequent growth and development in children [34] and as shown in the present study *in utero* exposure to cigarette smoke in mice results in lower body weight and TGV at 2 weeks of age.

There is also a relationship between urine cotinine levels (a stable metabolite of nicotine) and birth weight with increasing urine cotinine being associated with reduced birth weight [30]. Urine cotinine levels similar to those measured in our study (i.e. $\sim 5800 \text{ ng.mL}^{-1}$) resulted in a reduction in birth weight of $\sim 10\text{-}12\%$, which is almost identical to the reduction we measured [30]. Further, it has been shown that levels of cotinine in human urine are $\sim 5200 \text{ ng mL}^{-1}$ in adults who smoke 20-60 cigarettes per day [31], suggesting that our exposure protocol is equivalent to a similar exposure.

Most human studies which investigate the effects of *in utero* tobacco smoke exposure on lung function at birth, or in early life, account for birth weight in their analyses [8, 12, 35-37]. Generally, these studies find effects of *in utero* tobacco smoke exposure on lung function shortly after birth even when differences in birth weight are taken into account. Such studies are forced to try to correct for a plethora of confounders other than birth weight, including gestational age, parental atopy, passive or active smoking and smoking habits (i.e. number of cigarettes per day), all of which can influence the lung function of newborns. Using a mouse model of *in utero* cigarette smoke exposure allows us to eliminate the effects of these potential confounders.

In our study, CS pups showed impaired lung mechanics with the lungs at rest at the elastic equilibrium volume (greater R_{aw} , G , H and η) compared to Air pups, however, the impairments were attributable to size differences. The smaller overall size, and hence smaller lungs of CS pups will inherently “cause” apparent impairment in lung function as measured by our techniques. When differences in size are accounted for, CS pups appear to have “normal” lung function, however having significantly smaller lungs is, in itself, enough to have significant impacts on later lung health [38]. Further, our histological measures showed

that lung structure was not altered by *in utero* cigarette smoke exposure even though one might expect the lower TGV of CS pups to be associated with changes in lung structure. These findings strongly suggest that the smaller lung size of CS pups is the primary factor impacting their lung function.

An important finding of our study is the significant influence of *in utero* cigarette smoke exposure on the volume dependency of lung mechanics, whereby measures of tissue mechanics (G and H) were significantly higher in CS pups compared to Air pups when the lungs were inflated to a P_{rs} of 20cm H₂O. This impairment was apparent even when differences in TGV were taken into account. This characteristic has been largely overlooked in the literature to date, and may have important implications on how the potential effects of *in utero* tobacco smoke exposures are assessed in both animals and humans. For example, a higher G in CS pups indicates that they have greater resistance in the peripheral airways and reduced lung compliance compared to Air pups. Further, a higher G could reflect a greater proportion of closed peripheral lung units [39] or an increase in parallel airway heterogeneity [40, 41]. Closed lung units and increased airway heterogeneity could significantly impact overall lung health as these features reflect smaller airways in general, which can result in increased risk of respiratory infections, wheeze and other respiratory disease [38]. Our estimates of G, H and η include the mechanical contribution of the chest wall in addition to the lung tissue [42]. In adult mice, the chest wall contributes ~20% to G, but negligibly to H in adult mice. This contribution is likely to be considerably less in the 2 week old mice in our study where the chest wall is softer, however the potential contribution should not be ignored.

In conclusion, we measured significant differences in the lung mechanics of 2 week old BALB/c pups born to mothers exposed to cigarette smoke during pregnancy, compared to

controls. The greatest impacts stem from the smaller size and smaller TGV of CS pups. These changes may partially explain the increased susceptibility of infants born to mothers who smoke to early respiratory disease and chronic respiratory disease later in life. As such, additional studies investigating whether the measured deficits in size and TGV of mouse pups born to mothers exposed to cigarette smoke during pregnancy are maintained throughout life would be useful. Our findings are supported by epidemiological studies, which show significant impacts of cigarette smoke exposure on intrauterine and postnatal growth in humans [43]. Smaller lungs, and hence smaller airways in early life also increase the risk of respiratory viral infections, altered lung function, wheeze and other respiratory disorders [35, 44]. Further, impaired lung development *in utero* has been linked to COPD in later life [45]. These findings indicate that insults to the developing foetus can have significant repercussions to respiratory health in later life, regardless of whether the *in utero* insults directly affect the developing lungs.

Grants

This research was supported by an Asthma Foundation of Western Australia New Investigator Grant and by the National Health & Medical Research Council of Australia.

References

1. Cunningham J, Dockery DW, Speizer FE. Maternal Smoking during Pregnancy as a Predictor of Lung Function in Children. *Am J Epidemiol* 1994; 139(12): 1139-1152.
2. DiFranza JR, Aligne CA, Weitzman M. Prenatal and postnatal environmental tobacco smoke exposure and children's health. *Pediatrics* 2004; 113(4): 1007.
3. Gilliland FD, Berhane K, McConnell R, Gauderman WJ, Vora H, Rappaport EB, Avol E, Peters JM. Maternal smoking during pregnancy, environmental tobacco smoke exposure and childhood lung function. *Quality & Safety in Health Care* 2000; 55(4): 271.
4. Gilliland FD, Li Y, Peters JM. Effects of maternal smoking during pregnancy and environmental tobacco smoke on asthma and wheezing in children. *Am J Respir Crit Care Med* 2001; 163(2): 429.
5. Gilliland FD, Berhane K, Li Y, Rappaport EB, Peters JM. Effects of early onset asthma and in utero exposure to maternal smoking on childhood lung function. *Am J Respir Crit Care Med* 2003; 167(6): 917.
6. Lannero E, Wickman M, Pershagen G, Nordvall L. Maternal smoking during pregnancy increases the risk of recurrent wheezing during the first years of life (BAMSE). *Respiratory Research* 2006; 7: 3.
7. Li Y, Gilliland FD, Berhane K, McConnell R, Gauderman WJ, Rappaport EB, Peters JM. Effects of in utero and environmental tobacco smoke exposure on lung function in boys and girls with and without asthma. *Am J Respir Crit Care Med* 2000; 162(6): 2097.
8. Lodrup Carlsen KC, Jaakkola JJ, Nafstad P, Carlsen KH. In utero exposure to cigarette smoking influences lung function at birth. *The European Respiratory Journal* 1997; 10(8): 1774.
9. Singh SP, Barrett EG, Kalra R, Razani-Boroujerdi S, Langley RJ, Kurup V, Tesfaigzi Y, Sopori ML. Prenatal cigarette smoke decreases lung cAMP and increases airway hyperresponsiveness. *Am J Respir Crit Care Med* 2003; 168(3): 342.
10. Zlotkowska R, Zejda JE. Fetal and postnatal exposure to tobacco smoke and respiratory health in children. *Eur J Epidemiol* 2005; 20(8): 719.
11. Martinez FD, Cline M, Burrows B. Increased incidence of asthma in children of smoking mothers. *Pediatrics* 1992; 89(1): 21.
12. Stick SM, Burton PR, Gurrin L, Sly PD, Le Souef PN. Effects of maternal smoking during pregnancy and a family history of asthma on respiratory function in newborn infants. *The Lancet* 1996; 348(9034): 1060.
13. Seymour BWP, Friebertshauser KE, Peake JL, Pinkerton KE, Coffman RL, Gershwin LJ. Gender differences in the allergic response of mice neonatally exposed to environmental tobacco smoke. *Dev Immunol* 2002; 9(1): 47.
14. Barrett EG, Wilder JA, March T, H., Espindola T, Bice DE. Cigarette smoke-induced airway hyperresponsiveness is not dependent on elevated immunoglobulin and eosinophilic inflammation in a mouse model of allergic airway disease. *Am J Respir Crit Care Med* 2002; 165(10): 1410.
15. Bowles KS, Horohov DW, Paulsen DB, LeBlanc CJ, Littlefield-Chabaud MA, Ahlert T, Ahlert K, Pourciau SS, Penn A. Exposure of adult mice to environmental tobacco smoke fails to enhance the immune response to inhaled antigen. *Inhal Toxicol* 2005; 17(1): 43.
16. Joad JP, Ji CM, Kott KS, Bric JM, Pinkerton KE. In utero and postnatal effects of sidestream cigarette smoke exposure on lung function, hyperresponsiveness, and neuroendocrine cells in rats. *Toxicol Appl Pharmacol* 1995; 132(1): 63.
17. Joad JP, Pinkerton KE, Bric JM. Effects of sidestream smoke exposure and age on pulmonary function and airway reactivity in developing rats. *Pediatr Pulmonol* 1993; 16(5): 281.

18. Janosi TZ, Adamicza A, Zosky GR, Asztalos T, Sly PD, Hantos Z. Plethysmographic estimation of thoracic gas volume in apneic mice. *J Appl Physiol* 2006: 101(2): 454.
19. Sly PD, Collins RA, Thamrin C, Turner DJ, Hantos Z. Volume dependence of airway and tissue impedances in mice. *J Appl Physiol* 2003: 94(4): 1460-1466.
20. Fredberg JJ, Stamenovic D. On the imperfect elasticity of lung tissue. *J Appl Physiol* 1989: 67(6): 2408-2419.
21. Petak F, Hantos Z, Adamicza A, Asztalos T, Sly PD. Methacholine-induced bronchoconstriction in rats: effects of intravenous vs. aerosol delivery. *J Appl Physiol* 1997: 82(5): 1479.
22. Hantos Z, Daroczy B, Suki B, Nagy S, Fredberg JJ. Input impedance and peripheral inhomogeneity of dog lungs. *J Appl Physiol* 1992: 72(1): 168-178.
23. Hsia CCW, Hyde DM, Ochs M, Weibel ER, on behalf of the ATS/ERS Joint Task Force on the Quantitative Assessment of Lung Structure. An Official Research Policy Statement of the American Thoracic Society/European Respiratory Society: Standards for Quantitative Assessment of Lung Structure. *Am J Respir Crit Care Med*: 181(4): 394-418.
24. Nyengaard JR, Gundersen HJG. Sampling for stereology in lungs. *European Respiratory Review* 2006: 15(101): 107-114.
25. Simpson WJ. A preliminary report on cigarette smoking and the incidence of prematurity. *Obstet Gynecol Surv* 1957: 12(6): 868.
26. Macarthur C, Knox EG. Smoking in pregnancy: effects of stopping at different stages. *BJOG: An International Journal of Obstetrics & Gynaecology* 1988: 95(6): 551-555.
27. Kramer MS. Intrauterine growth and gestational duration determinants. *Pediatrics* 1987: 80(4): 502.
28. Kramer MS, Olivier M, McLean FH, Dougherty GE, Willis DM, Usher RH. Determinants of fetal growth and body proportionality. *Pediatrics* 1990: 86(1): 18.
29. Meyer MB, Comstock GW. Maternal cigarette smoking and perinatal mortality. *Am J Epidemiol* 1972: 96(1): 1.
30. England LJ, Kendrick JS, Gargiullo PM, Zahniser SC, Hannon WH. Measures of Maternal Tobacco Exposure and Infant Birth Weight at Term. *Am J Epidemiol* 2001: 153(10): 954-960.
31. Biber A, Scherer G, Hoepfner I, Adlkofer F, Heller W-D, Haddow JE, Knight GJ. Determination of nicotine and cotinine in human serum and urine: An interlaboratory study. *Toxicol Lett* 1987: 35(1): 45-52.
32. Bush PG, Mayhew TM, Abramovich DR, Aggett PJ, Burke MD, Page KR. Maternal Cigarette Smoking and Oxygen Diffusion Across the Placenta. *Obstet Gynecol Surv* 2001: 56(6): 324.
33. Morrow RJ, Ritchie JW, Bull SB. Maternal cigarette smoking: the effects on umbilical and uterine blood flow velocity. *Am J Obstet Gynecol* 1988: 159(5): 1069.
34. Barros FC, Huttly SRA, Victora CC, Kirkwood BR, Vaughan JB. Comparison of the causes and consequences of prematurity and intrauterine growth retardation: a longitudinal study in southern Brazil. *Pediatrics* 1992: 90(2): 238.
35. Hanrahan JP, Tager IB, Segal MR, Tosteson TD, Castile RG, Van Vunakis H, Weiss ST, Speizer FE. The effect of maternal smoking during pregnancy on early infant lung function. *Am J Respir Crit Care Med* 1992: 145(5): 1129.
36. Tager IB, Ngo L, Hanrahan JP. Maternal smoking during pregnancy. Effects on lung function during the first 18 months of life. *Am J Respir Crit Care Med* 1995: 152(3): 977.
37. Young S, Le Souef PN, Geelhoed GC, Stick SM, Turner KJ, Landau LI. The influence of a family history of asthma and parental smoking on airway responsiveness in early infancy. *The New England Journal of Medicine* 1991: 324(17): 1168.

38. Barker DJ, Godfrey KM, Fall C, Osmond C, Winter PD, Shaheen SO. Relation of birth weight and childhood respiratory infection to adult lung function and death from chronic obstructive airways disease. *Br Med J* 1991; 303(6804): 671-675.
39. Lutchen KR, Gillis H. Relationship between heterogeneous changes in airway morphometry and lung resistance and elastance. *J Appl Physiol* 1997; 83(4): 1192.
40. Lutchen KR, Greenstein JL, Suki B. How inhomogeneities and airway walls affect frequency dependence and separation of airway and tissue properties. *J Appl Physiol* 1996; 80(5): 1696.
41. Lutchen KR, Hantos Z, Petak F, Adamicza A, Suki B. Airway inhomogeneities contribute to apparent lung tissue mechanics during constriction. *J Appl Physiol* 1996; 80(5): 1841.
42. Bozanich EM, Collins RA, Thamrin C, Hantos Z, Sly PD, Turner DJ. Developmental changes in airway and tissue mechanics in mice. *J Appl Physiol* 2005; 99(1): 108-113.
43. Hofhuis W, de Jongste JC, Merkus PJFM. Adverse health effects of prenatal and postnatal tobacco smoke exposure on children. *Arch Dis Child* 2003; 88(12): 1086-1090.
44. Dezateux C, Stocks J, Dundas I, Fletcher ME. Impaired Airway Function and Wheezing in Infancy The Influence of Maternal Smoking and a Genetic Predisposition to Asthma. *Am J Respir Crit Care Med* 1999; 159(2): 403.
45. Coultas DB. Health effects of passive smoking-8: Passive smoking and risk of adult asthma and COPD: an update. *Thorax* 1998; 53(5): 381.

Figure Legends

Figure 1 – The relationship between body mass (g) and thoracic gas volume (mL) for two week old mice born from mothers exposed to mainstream cigarette smoke during pregnancy (black circles, $n = 17$) and controls (white circles, $n = 20$). Each circle represents an individual pup. Pups born from mothers exposed to mainstream cigarette smoke during pregnancy have significantly lower TGV for a given mass compared to control pups ($p < 0.001$).

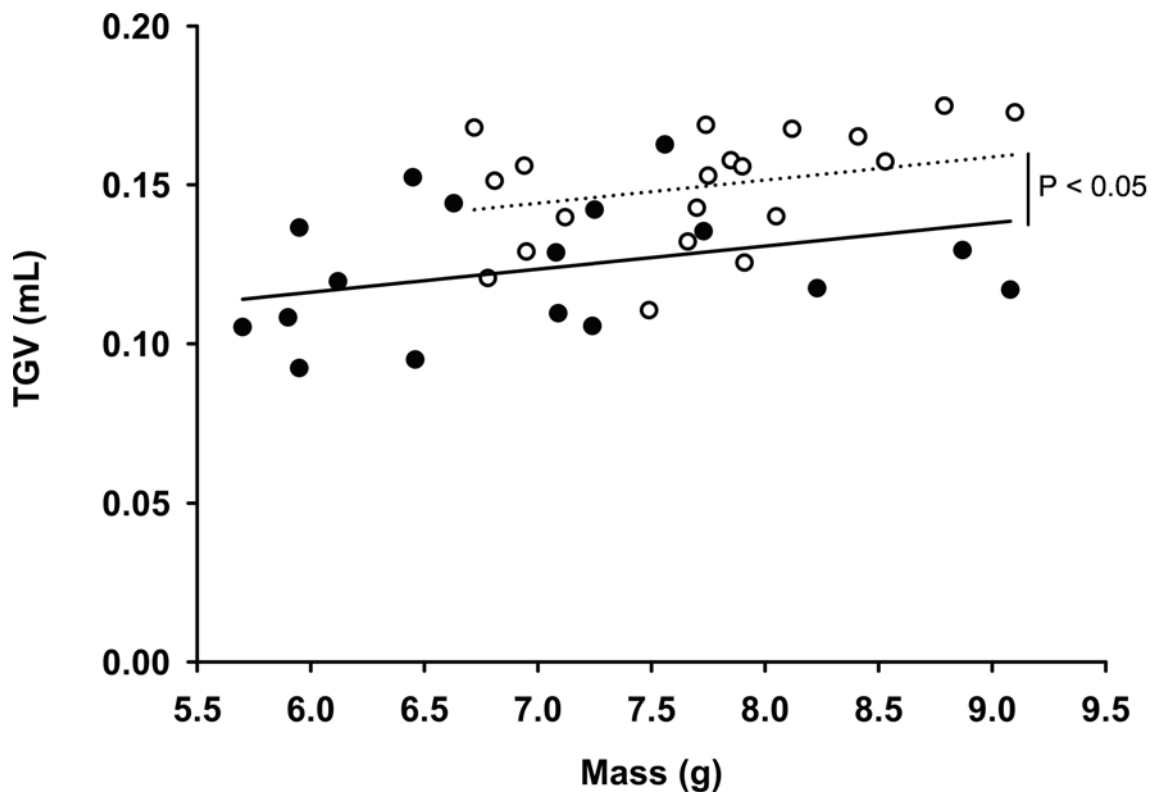


Figure 2 – Baseline lung mechanics (airway resistance – R_{aw} , tissue damping – G and tissue elastance – H) for two week old BALB/c pups exposed to mainstream cigarette smoke *in utero* (black circles, $n = 17$) and controls (white circles, $n = 20$). Each circle represents an individual pup.

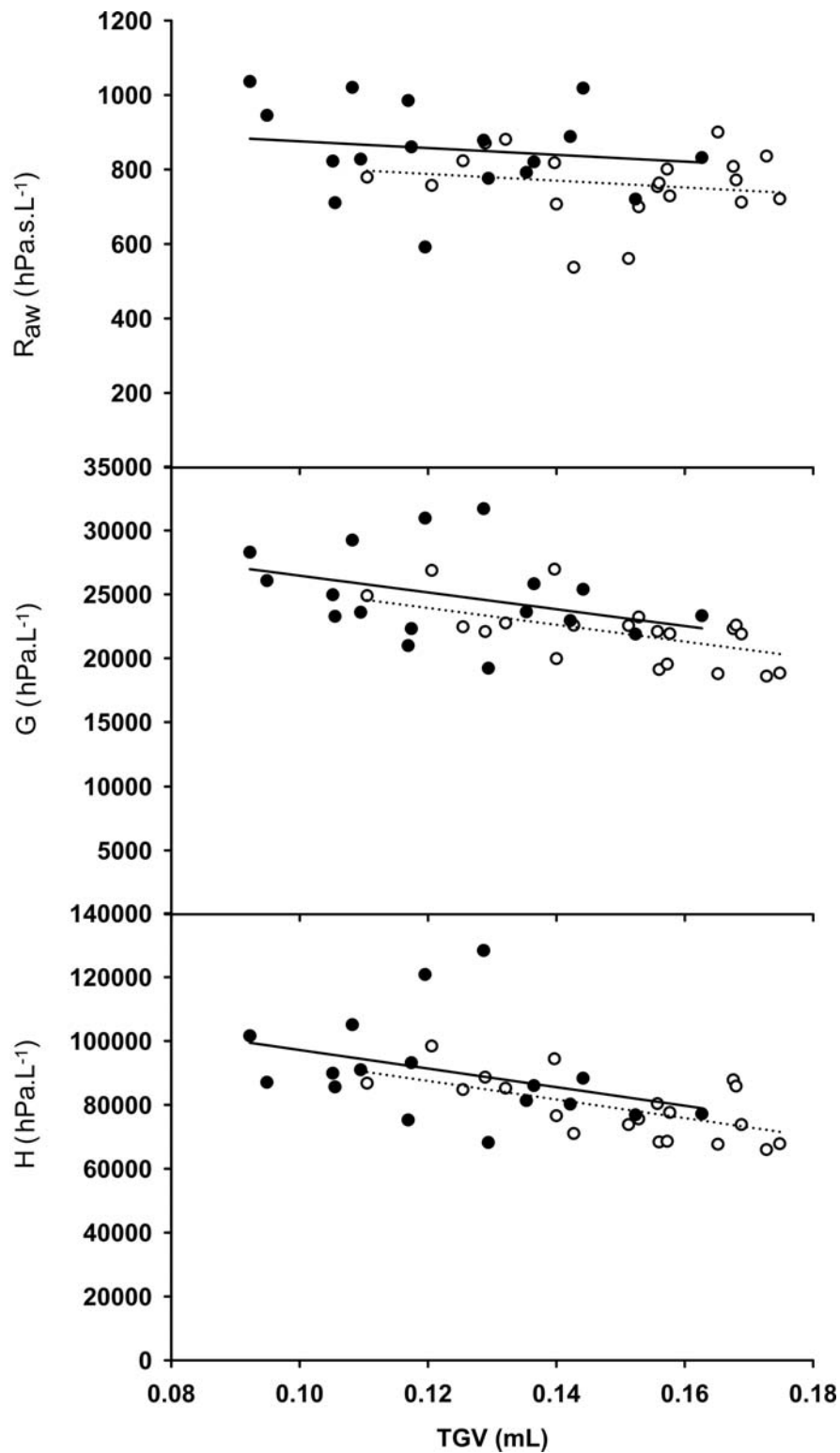


Figure 3 – Mean pressure-volume (PV) curves for inflation-deflation maneuvers for two week old pups exposed to cigarette smoke *in utero* (black circles, n = 17) and control pups (white circles, n = 20) starting at 0cm H₂O transrespiratory pressures up to 20 cm H₂O. The maximum TGV reached for CS pups was significantly less than that reached for Air pups (p < 0.05). Data are group means (SD).

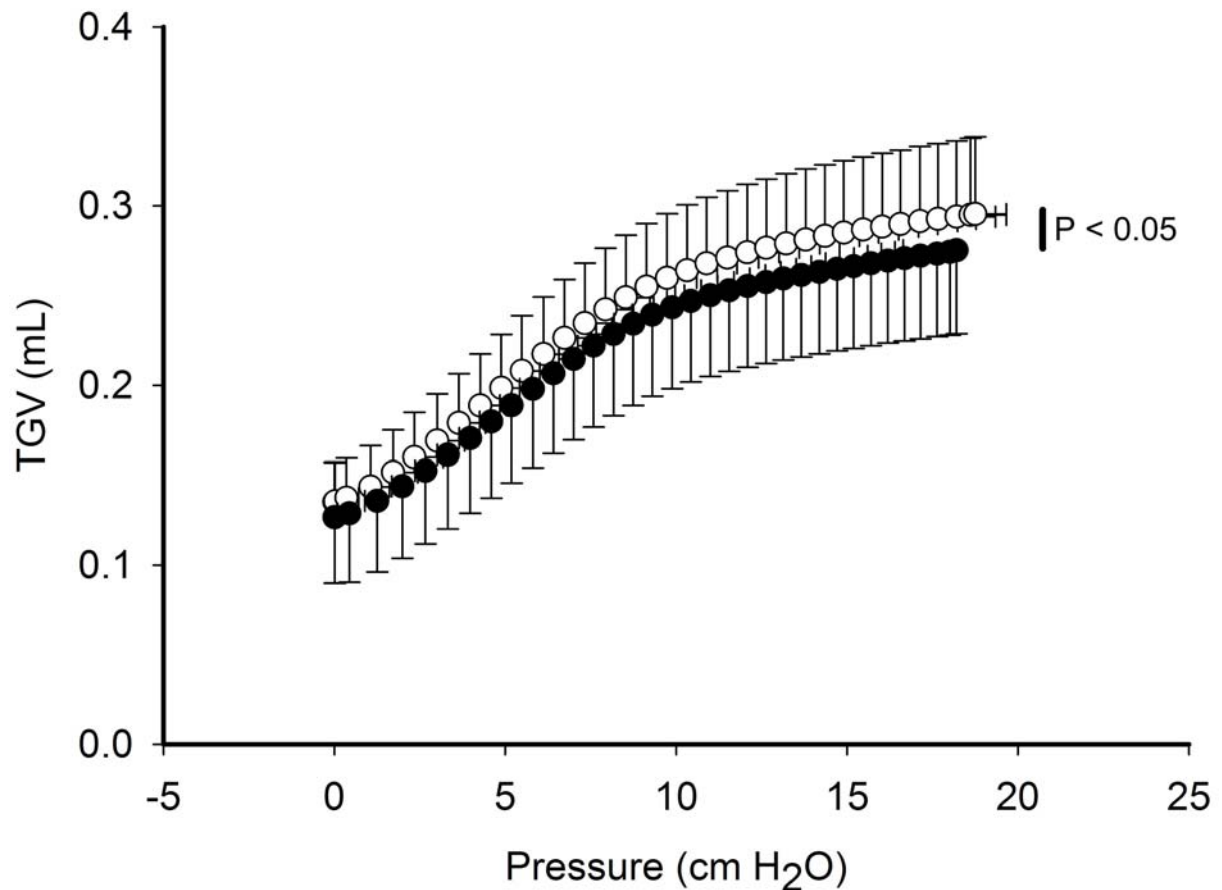
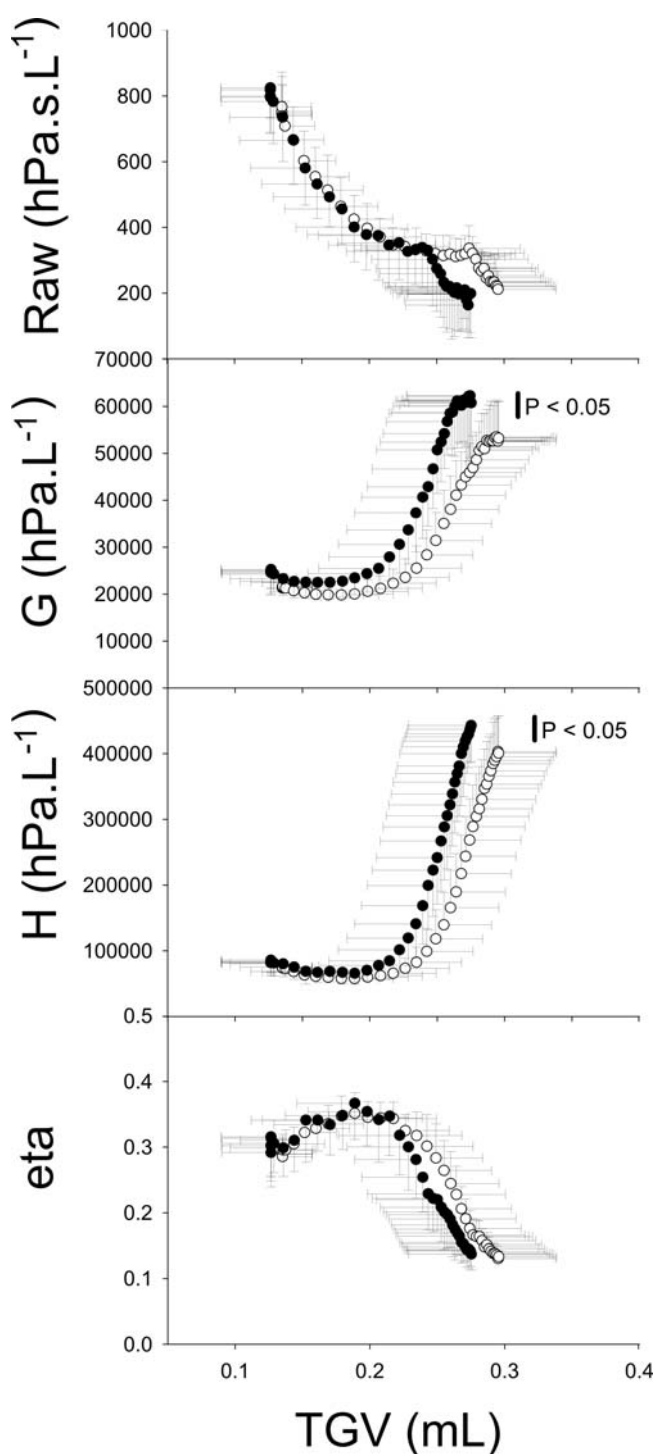


Figure 4 – Influence of *in utero* mainstream cigarette smoke exposure on airway resistance (R_{aw}), tissue damping (G), tissue elastance (H) and hysteresivity (eta) of 2 week old pups during forced inflation from transrespiratory pressure (P_{rs}) of 0 to 20 cmH₂O. Black circles = two week old pups exposed to cigarette smoke *in utero* (mean of n = 17) and white circles = two week old control pups (mean of n = 20). Data are means (SD).



Supplementary Figure 1 – Stepwise decrease in plethysmographic box pressure as a vacuum source is applied, displaying that the box is airtight when required for measurement of thoracic gas volume (A), a representative thoracic gas volume trace showing negligible thermal drift during measurement (B) and the relationship between plethysmographic box pressure and tracheal pressure for the TGV trace shown above indicating strong correlation between these two measurements.

