RESEARCH PAPER

Flying the smoky skies: secondhand smoke exposure of flight attendants

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Tobacco Control 2004;**13**(Suppl I):i8–i19. doi: 10.1136/tc.2003.003111

Objective: To assess the contribution of secondhand smoke (SHS) to aircraft cabin air pollution and flight attendants' SHS exposure relative to the general population.
Methods: Published air quality measurements, modelling studies, and dosimetry studies were reviewed, analysed, and generalised.
Results: Flight attendants reported suffering greatly from SHS pollution on aircraft. Both government and airline sponsored studies concluded that SHS created an air pollution problem in aircraft cabins, while tobacco industry sponsored studies yielding similar data concluded that ventilation controlled SHS, and that SHS pollution levels were low. Between the time that non-smoking sections were established on US carriers in 1973, and the two hour US smoking ban in 1988, commercial aircraft ventilation rates had declined three times as fast as smoking prevalence. The aircraft cabin provided the least volume and lowest ventilation rate per smoker of any social venue, including stand up bars and smoking lounges, and afforded an abnormal respiratory environment. Personal monitors showed little difference in SHS exposures between flight attendants assigned to smoking sections and those assigned to non-smoking sections of aircraft cabins.
Conclusions: In-flight air quality measurements in ~250 aircraft, generalised by models, indicate that when smoking was permitted aloft, 95% of the harmful respirable suspended particle (RSP) air pollution in the smoking sections and 85% of that in the non-smoking sections of aircraft cabins was caused by SHS. Typical levels of SHS-RSP on aircraft violated current ($PM_{2.5}$) federal air quality standards ~threefold for flight attendants, and exceeded SHS irritation thresholds by 10 to 100 times. From cotinine dosimetry, SHS exposure of typical flight attendants in aircraft cabins is estimated to have been >6-fold that of the average US worker and ~14-fold that of the average person. Thus, ventilation systems massively failed to control SHS air pollution in aircraft cabins. These results have implications for studies of the past and future health of flight attendants.

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Flight attendants have worked on aircraft since 1931. By 1985 there were 40 000 flight attendants employed by US airlines,[1] and by 2000, the number had increased to almost 116 000.[2] For years, flight attendants reported health problems they attributed to their occupational exposures. Yet, as recently as the mid 1980s, little had been done to characterise either the quality of the air in airliner cabins or its possible health effects on cabin crew, and there were no federal standards governing secondhand smoke (SHS) exposure.[1] Smoking in the USA was unrestricted on commercial passenger aircraft until 1973, when the US Civil Aeronautics Board (CAB) imposed regulations to separate smoking passengers from non-smoking passengers by establishing non-smoking sections on the basis of numerous complaints from passengers.[3] However, in 1986, the National Academy of Sciences recommended a ban on smoking on domestic flights,[1] and contemporaneously, both the Surgeon General[4] and the National Academy of Sciences[5] concluded that SHS caused lung cancer.

Most published air quality studies of SHS on aircraft were conducted after 1987, and no further regulation took place until 1988, when a US Congressionally mandated smoking ban took effect on domestic airline flights scheduled for two hours or less.[6] At that time, Northwest Airlines voluntarily banned smoking on all its North American flights. In 1989, mainly based on complaints by flight attendants, the US Congress imposed a broader smoking ban on all US domestic flights of six hours duration or less.[6] Subsequently, many airlines voluntarily banned smoking on flights longer than six hours, and by 1999, a reported 97% of flights to and from the US were smoke-free.[7] However, as recently as 1998, some US airlines, including Northwest, continued to permit smoking on their US based international flights to the Orient. Flight attendants exposed on such flights often encountered smoking prevalence far higher than on other routes.[8]

Because of complaints about poor air quality on aircraft, especially about SHS, a number of studies have measured airborne contaminants in aircraft cabins. The major pollutant emitted by tobacco smoking is respirable suspended particles (RSP), which, while not unique to SHS, typically dwarfs indoor air concentrations from other sources of RSP, and therefore is often used as an atmospheric tracer for SHS.[1 9 10] Nicotine, although much less copiously emitted than RSP, is a unique atmospheric tracer for SHS, and its metabolite, cotinine, is the definitive biomarker for SHS dose. Air pollution concentrations from SHS on passenger aircraft are determined by the ratio of the smoker density (time averaged number of cigarettes smoked per unit volume) to the air

Abbreviations: ASHRAE, American Society of Heating, Refrigerating, and Air Conditioning Engineers; CAB, Civil Aeronautics Board; CDC, Centers for Disease Control; FAA, Federal Aviation Administration; NAS, National Academy of Sciences; NCI, National Cancer Institute; RSP, respirable suspended particles; SHS, secondhand smoke; TSP, total suspended particles; VOC, volatile organic compounds exchange rate supplied by aircraft ventilation systems.[9] SHS dose is determined by the product of the smoke concentration to which persons are exposed, their respiration rates during exposure, and the duration of their exposure.

This paper reviews RSP and nicotine measurements on ~250 passenger aircraft as variously studied by the government, the airlines, non-governmental organisations, and the tobacco industry, as well as one federal study of cotinine dosimetry in flight attendants, emphasising post-1985 studies. The results of three modelling studies are reviewed to generalise the RSP data. This work also examines how various groups interpreted their data in terms of SHS policy, and for the first time, compares flight attendants' SHS doses on aircraft to SHS doses of the general US population. Finally, flight attendants historic SHS exposure is interpreted in light of late 1990s federal air quality standards, and a 21st century study of irritation from SHS.

AIRCRAFT VENTILATION SYSTEMS

The first flight attendants flew on unpressurised propeller aircraft on low altitude flights. In the mid-1940s, pressurisation systems were introduced, and unfiltered cabin air recirculation systems were adopted to augment cabin airflow.[7] Pressurisation of aircraft cabins permitted operation at higher altitudes, which substantially reduced aircraft drag and hence propulsion fuel costs.[11] In the 1950s, the first commercial passenger jets, the B-707 and DC-8, were introduced. In the mid-1970s, B-747s began flying polar routes. By the early 1980s the majority of new transport aircraft employed a combination of engine bleed (outside) air coupled with filtered recirculated air in order to conserve fuel. Today, about 50% of commercial passenger aircraft use recirculated air; however, as the energy cost of cooling hot engine bleed air for ventilation has increased, this has led to a significant decrease in the amount of outside air provided to the passenger cabin.[7 11 12] For example, while the DC-10's nominal air exchange rates range from 7 to 21 cubic feet per minute per passenger (ft^3/min per passenger), reduced flow valves permitted reducing these flow rates to a half to two thirds of normal, and on some planes, shutting down one of three ventilation packs.[1] This is also possible—and was done in practice—on wide body three pack models of Boeing aircraft, such as the B-747 and the B-767.[12–14] About 62 000 gallons of fuel could be saved annually for each 10 ft^3/min per passenger reduction in an aircraft's ventilation rate.[1] This practice is believed to be widespread in the economically troubled airline industry. Until 1996, US Federal Aviation Administration (FAA) regulations provided only that the airliner cabin passenger compartment ''must be suitably ventilated'',[15 58] and since 1996, have provided only that passenger cabin ventilation systems be designed (not operated) to provide 0.55 lbs of outside air per design occupant (equivalent to 10 ft^3/min per occupant at 8000 feet of cabin pressure and 22°C cabin temperature).[58]

In 1970, the typical passenger aircraft provided 15 ft^3/min (7 litres/s) or more of outside air per person, but by 1987, this had declined to where some new commercial aircraft provided barely 6 ft^3/min per person (2.8 litres/s per person) of outside air flow to their passenger cabins.[11] Moreover, at the pilot's discretion, aircraft manufactured during the 1970s could reduce outside airflows to 10 ft^3/min per person, and outside air delivery rates have been reduced to as low as 2.1 ft^3/min per person (1 litre/s per person), or ~1/10 of that for office workers.[11 16] For example, one study of ventilation rates on seven aircraft, model unidentified, but seating up to 101 passengers, found that on 45 flights of one hour or less, whenever the number of passengers exceeded 34, the ventilation failed to meet the manufacturers' recommendation of 5 litres/s per passenger.[16] For aircraft with particulate air filtration, nominal filter efficiency (90–99.98%) varies with airline policy; however, such efficiencies are not attained in practice.[11] Gaseous SHS contaminants are not filtered. Thus, aircraft ventilation rates have declined by a third to half or more since 1970.

In addition to low per person air exchange rates, aircraft cabins have the smallest available airspace per person of any social venue, and occupants of a fully loaded aircraft typically have about 35–70 ft^3 (1–2 m^3) of available airspace per person, < 1/10th that of a typical office worker or a spectator in an auditorium.[11] Moreover, aircraft cabins have an abnormal respiratory environment relative to most human habitats: they typically are pressurised to only ~75% that at sea level, equivalent to an altitude of 8000 ft (2440 m); at such a pressure, there is a lower oxygen partial pressure than at sea level.[11 17] In addition, the upper limits on carbon dioxide concentrations in aircraft are five times higher than in buildings.[12] The combination of lower partial pressure of oxygen, high carbon dioxide concentrations, and very low humidity in aircraft cabins may increase respiratory system stress and irritation for persons in aircraft cabins aloft relative to those at or near sea level, especially for non-sedentary flight attendants.[3 12 18 52 58]

SECONDHAND SMOKE POLLUTION IN AIRCRAFT CABINS

The second major factor in determining air quality on passenger aircraft is the strength of pollutant sources. A typical cigarette emits an average of 14 mg of RSP when smoked.[54] The US national average smoking rate was two cigarettes per hour in 1980[9] and only 10% less by 1990. Despite the fact that smoking emits copious amounts of toxic air pollutants into a small cabin volume, for most of the history of commercial air travel, smoking has been taken for granted. The volume of the aircraft and the maximum person density are fixed by the aircraft design. Thus, the cabin smoker density is essentially dependent upon the number of passengers and the smoking prevalence and smoking rate among those passengers. The overall US population smoking prevalence was 37% in 1970, 33% in 1980, and by 1987, had declined only slightly to 29%.[4] However, in 1986, the proportion of airline passengers who smoked and requested seating in the smoking section was estimated at 32.3%,[1] a reduction by only 13% from the 1970 smoking prevalence.

In 1986, the National Academy of Sciences[1] warned that: ''ETS [SHS is also called environmental tobacco smoke or ETS] is a hazardous substance and is the most frequent source of complaint about aircraft air quality.'' …''Because of the high concentration of ETS generated in the smoking zone, it cannot be compensated for by increased ventilation in that zone. Moreover, …smoking and non-smoking zones do not prevent exposure of flight attendants … to ETS, because of the location of galleys and lavatories in the smoking areas. Smoke exposure can become significant in aircraft with outside-air flow rates as low as 7 ft^3/min/passenger. Even a ventilation rate of 14–15 ft^3/min/passenger consists of as much as 50% recirculated, and possibly smoky, cabin air.''…''the Committee feels that this potential threat to the health of…flight attendants should not be ignored.'' …''It is highly probable that eye, nose, and throat irritation will increase … as outside air ventilation rates are decreased and recirculation is increased to improve fuel efficiency.'' ''The Committee recommends a ban on smoking on all domestic commercial flights…to lessen irritation and discomfort to…crew, to reduce potential health hazards to cabin crew associated with ETS, to eliminate…fires, and to bring the cabin air quality into line with established standards for other closed environments.''

MEASUREMENTS OF SECONDHAND SMOKE

A literature search disclosed a number of measurements of airliner cabin air quality conducted between 1971 and 1998 variously by the government, by the airline industry, and by the tobacco industry. Measurements variously included air pressure, bioaerosols, carbon monoxide (CO), carbon dioxide (CO_2), formaldehyde, ionizing radiation, nicotine, ozone, relative humidity, total or respirable particulate matter (TSP or RSP), ventilation rates, and volatile organic compounds (VOC).[1 14] The best indicators for SHS are gas phase nicotine and RSP. Nicotine is strongly correlated to both gas and particulate phase SHS compounds[20]; both gas-phase and particulate phase SHS contain many potent carcinogens and toxins. Data from studies of RSP and nicotine on aircraft since 1971 are summarised in tables 1, 2, and 3. These are identified as those sponsored by the airlines, by government, by non-governmental organisations, and by the tobacco industry, and their conclusions discussed below.

GOVERNMENT SPONSORED STUDIES

The National Academy of Sciences (NAS) Committee on Airliner Cabin Air Quality study[1] was commissioned by Congress under Public Law 98–466 as a result of hearings in 1983–84 that revealed that available data on airliner cabin air quality were contradictory. The regulatory community and the airline industry then asserted that industry standards and practices were adequate and that the aircraft environment did not endanger either the health or safety of passengers or crew. The NAS Committee on Airliner Cabin Air Quality reviewed data on air quality, cabin pressure, humidification, cosmic radiation, microorganisms, and pollutants including carbon monoxide, carbon dioxide, ozone, and ETS. The committee noted that aircraft air quality had not been a subject of systematic investigation, but that various airlines had conducted tests, and the committee conducted some spot measurements, generalised by mathematical modelling. The 303 page NRC report recommended that smoking on all domestic flights be banned for four major reasons: to lessen irritation and discomfort for passengers and crew; to reduce potential health hazards to cabin crew from SHS; to eliminate potential fire hazards; and to bring the cabin air quality into line with established standards for other closed environments. The committee pointedly concluded that the lowest rate of cabin ventilation under conditions of nearly full occupancy would be the minimum to provide acceptable air quality when neither SHS nor other (physical) contaminant sources were present.

In a 1989 study funded by the National Cancer Institute, Mattson *et al*[21] measured personal nicotine concentrations and urinary cotinine in four flight attendants and five passengers on four, 4 hour Air Canada transcontinental flights, two B-727's, and two B767's. Mattson *et al* found that attendants assigned to work in non-smoking areas were not protected from smoke. Self reported eye and nasal symptoms and perception of a smoky atmosphere were significantly related to nicotine and cotinine, and both were correlated to annoyance as well, although the positive cotinine trend was not significant. Mattson *et al*[21] concluded that SHS exposures on aircraft create a health risk, acute irritation, and annoyance to non-smokers.

In 1989, the US Department of Transportation sponsored the first comprehensive study of airliner cabin air quality.[3 22] Its purpose was ''to develop information to be used for determining health risks from exposure to SHS and other pollutants for airliner occupants''. Selected SHS contaminants (nicotine, RSP, CO) as well as CO_2, ozone (O_3), microbial aerosols, cabin pressure, relative humidity, and temperature were measured in 92 randomly selected aircraft. Both RSP and nicotine correlated strongly with observed smoking rates, and under actual operating conditions, variability in the overall average SHS-RSP to SHS-nicotine ratio was small, yielding a range of 11.0–12.5.

For all smoking flights, domestic and international, the average number of passengers in the smoking section was 18, and ranged from 2–63; the average percentage of passengers in the smoking section was 13.7%, and ranged from 1.4–41.9%, and the average number of cigarettes smoked per passenger hour was 1.5 (range 0.2–6.5).[3] There was evidence for migration of SHS-RSP into the non-smoking sections. Ozone levels were well within standards, while relative humidity averaged $< 16\%$, and cabin pressure averaged 661 mm Hg (760 mm Hg is sea level). Ventilation rates did not limit CO_2 levels to the ASHRAE (American Society of Heating, Refrigerating, and Air Conditioning Engineers) standard for comfort of 1000 ppm. Nagda *et al*[3] generalised their measurements by mathematical modelling, and conducted a carcinogen risk assessment using two dose–response models. Nagda *et al* recommended a total or partial ban on smoking as ''measured values…were well within the range associated with irritancy response and unacceptable cancer risk for the general population''.[19]

For eight randomly selected international flights, RSP results reported by Nagda *et al*[3 22] are given in fig 1. Figure 1 plots RSP concentration on smoking and non-smoking flights as a function of seating position with respect to the smoking section in the aircraft. These involved wide body aircraft, including five B747s, one B-767, and two MD DC10s.[3] The average load factor (per cent of seating capacity filled by passengers) was 64%.[3] Figure 1 shows that smoking elevates peak RSP levels by 100-fold, and average RSP levels by 15-fold in the smoking section, and that the non-smoking section (boundary, middle, and seats most remote from smoking) on smoking flights is considerably contaminated with fine particle pollution relative to non-smoking flights. Multiple studies on aircraft have reported[3] peak levels of fine particles, characteristic of SHS-RSP, in the range of 750–1200 $\mu g/m^3$. Such peaks assume even greater importance when flight attendants' activity patterns are taken into account: peaks appear to occur after meals while flight attendants may be servicing the cabin,[3] increasing proximity to smoking and elevating attendants' SHS doses beyond what area monitors of SHS concentrations would suggest. Such peaks assume greater import when acute irritating effects of tobacco smoke are considered.

A US National Institute for Occupational Safety & Health (NIOSH) study, performed by Waters *et al*[23] between 1995 and 1998, investigated cabin environmental contaminants on 36 US commercial aircraft, including a number of international flights. RSP levels were measured on smoking flights, but not on non-smoking flights. Peak levels of RSP in rear coach were substantially higher than front coach due to smoking (M Waters, personal communication). Gate-to-gate times varied from 42 to 863 minutes, and passenger occupancy in coach from 34% to 100% of capacity. CO_2 exposures (the higher the poorer the ventilation) were highest on shorter and high occupancy flights, aircraft with a higher degree of recirculation, and narrow bodied aircraft.[23] NIOSH concluded that CO_2 levels indicated lower ventilation rates per occupant than most other indoor environments, a likely result of the fact that commercial aircraft are not required by the Federal Aviation Administration to meet performance criteria with respect to either outside or recirculation air.[23]

AIRLINE STUDIES

In 1997, an SAS funded study by Lindgren *et al*[24] assessed perception of air quality by questionnaire in 1857 Stockholm based SAS aircrew and measured cabin air quality (RSP,

Table 1 Comparison of measured RSP pollution between smoking and non-smoking flights

Study author, year; number of flights; country; sponsor	Average RSP concentration ($\mu g/m^3$) smoking sections	Average RSP concentration ($\mu g/m^3$) non-smoking sections	Average RSP concentration ($\mu g/m^3$) non-smoking flights	Estimated % of smoking section RSP pollution from SHS	Comment
Malmfors *et al* (1989)[31]; n = 48; Sweden; tobacco industry	235† (SD 123)†	110† (SD 70)†	Not performed	–	1988 tobacco industry funded study on 48 SAS DC-9 and MD-80 flights; weighted average flight time of 1.8 hours
Nagda *et al* (1989)[3]; n = 92; USA; government	177 (SD 104)	25 (SD 23)	10.6 (SD 5.7)	94%	1989 US Department of Transportation study on 92 random smoking (n = 69; 61 domestic and 8 international) and non-smoking flights (n = 23); optical RSP values, table 4–16
Drake *et al* (1990)[51]; n = 4, Japan: tobacco industry	46 (SD 54)	17 (SD 17)	Not performed	–	1987 Philip Morris study on four B-747 international JAL smoking flights measured RSP in all classes and zones. Based on an analysis of data presented, with an average of 20.4 cigarettes/hour. Data as reported were lower: 38 $\mu g/m^3$ (SD NR) and 14 $\mu g/m^3$ (SD NR) respectively
Eatough *et al* (1992)[32]; n = 4; unknown; tobacco industry	155† (SD 61)†	68† (SD 57)†	Not performed	–	Tobacco industry funded controlled experiment on four 5 hour DC-10 smoking flights (airline not reported) at an air exchange rate of 30/h with zero recirculation of air
CSSI (1999), Pierce *et al* (1999)[18]; n = 8; USA; NGO	Not performed	–	<10‡	–	1998 ASHRAE study on 8 US non-smoking B777-200 flights seating 305 to 320, 4 domestic and 4 international
Waters *et al* (2002)[23]; n = 6; US; government	Not given	20–153 (range)	Not given	–	NIOSH study on 36 US domestic and international flights. Gate-to-gate times varied from 42–863 mins, and passenger occupancy in coach from 34% to 100% of capacity
Lindgren *et al* (2002)[25]; n = 26; Sweden; airline	49 (peak 253)		3 (SD NR)	94%	SAS funded study of aft galley area on 26 intercontinental flights of a B767-300. Number of smokers <20 to >30 on 19 smoking flights; number of passengers 122–190 on 7 non-smoking flights
Lindgren *et al* (2000)[24]; n = 6; Sweden; airline	67 (SD 61)		4 (SD 1)	94%	SAS funded study measured RSP on 6 B-767-300 intercontinental flights during 9 smoking and 8 non-smoking flight segments
Lee *et al* (2000)[15]; n = 16; Hong Kong; airline	138 (range 0–3000)		8 (range 0–300)	94%	Cathay Pacific Airways funded study on 16 flights, 3 smoking, 13 non-smoking on 3 aircraft: B747-400, Airbus-330, and Airbus-340
All, weighted means	168	59	8	95%	(n = 156) smoking; (n = 125) non-smoking sections; (n = 59) non-smoking flights

†Calculated from data; ‡level of detection = 10 $\mu g/m^3$.
All means are arithmetic with standard deviation, unless identified as geometric means as reported.
NGO, non-governmental organisation.

Table 2 Comparison of measured and modelled RSP pollution between smoking & non-smoking flights

Study author; country; sponsor	Average RSP concentration (µg/m³) smoking sections	Average RSP concentration (µg/m³) non-smoking sections	Average RSP concentration (µg/m³) non-smoking flights	Estimated % of smoking section RSP pollution from SHS	Comment
FAA & USPHS, 1970–1971 (NRC 1986)[1]; n = 34; USA; government	Average 140 µg/m³; peak 1200‡		NA†		"Several aircraft" one of the earliest studies: 20 military and 14 civilian flights
United Airlines, 1982 (NAS 1986)[1]; USA; airline	Range 54 (SD 24) to 264 (SD 101)		–		Maximum and minimum values averaged for five aircraft: B-747, DC-10, DC-8-61; B-727, B737 (unpublished data reported in NRC table 5-3) data do not specify sections
J Spengler (NAS, 1986)[1]; USA; NGO	Range 50–500 peak 1000	Range 10–50	NA		B-747 using piezobalance (unpublished data reported in NRC table 5-3)
J Spengler (NAS, 1986)[1]; USA; NGO	300 (SD 200) peak 750	100 (SD 20) forward 10–40 aft	NA		DC-10 using nephelometer load factors 40–60% six segments of a Boston-Anchorage flight (unpublished data reported in NRC table 5-3) load factor 40–60%
Models for RSP on aircraft					
Repace & Lowrey (1980)[9]; modelled concentration	167		–	–	B-707, 23 air changes/hour 100% load factor, 33% smoking prevalence, assumes flight attendants exposed to uniformly mixed concentration
NAS (1986)[1]; modelled concentration	500		–	–	B-767, coach 60% load factor 12.7 air changes/hour, 50% recirculation, 33% smoking prevalence; volume averaged concentration
Nagda *et al* (1989)[3]; modelled concentration	224	44	–	–	MD-80, 23 air changes/hour, 21% recirculated, 15 cigarettes/hour (observed) in 8 rows (21% of coach rows)
Nagda *et al* (1989)[3]; actual measurement	302	86	–	–	MD-80, 23 air changes/hour, 21% recirculation, 15 cigarettes/hr (observed) in 8 rows (21% of coach rows)
Nagda *et al* model[3]	122	5	–	–	B-727, 22 air changes/hour; 3 cigarettes/hour, 0% recirculation
Nagda *et al* measurement[3]	233	32	–	–	B-727, 22 air changes/hour; 3 cigarettes/hour, 0% recirculation

†Non-smoking flights did not exist at this time; ‡Non-smoking sections did not exist at this time.
All means are arithmetic with standard deviation, unless identified as geometric means as reported.

Table 3 Comparison of SHS nicotine in smoking and non-smoking sections of cabins of smoking flights

Study author; number of flights; country; sponsor	Average (SD) nicotine concentration (μg/m^3) smoking section	Average nicotine concentration (μg/m^3) non-smoking section	Average nicotine concentration (μg/m^3) non-smoking flight	% of smoking section nicotine infiltrating non-smoking section	Comment
Oldaker *et al* (1987)[30]; n = 3; unknown; tobacco industry	9.2 GM‡ 23† (SD 29)†	5.5 GM‡ 8.8† (SD 9.2)†	Not performed	60% (GM) 38% (AM)	1987 RJ Reynolds study: gas phase nicotine on 3 narrow bodied B727-200, B737-200, and B737-300 aircraft; 25 smoking section samples, 52 non-smoking section samples
Malmfors *et al* (1989)[31]; n = 48; Sweden: tobacco industry	36.5† (SD 22)†	13.0† (SD 11)†	Not performed	36%	1988 tobacco industry funded study on 48 SAS DC-9 and MD-80 flights; weighted average flight time of 1.8 hours
Nagda *et al* (1989)[3]; n = 61; USA; government, domestic flights	13.2 (SD 15)	0.12 (SD 0.22)	0.04	0.9%	1989 US Department of Transportation funded study on 92 random smoking (n = 69; 61 domestic and 8 international) and non-smoking flights (n = 23)
Nagda *et al* (1989)[3]; n = 8; USA; government, international flights	15.1 (SD 13.6)	0.46 (SD 0.82)	0.04	3%	
Mattson *et al* (1989)[21]; n = 4; Canada; government	15*	See text	Not performed	–	1989 National Cancer Institute study: personal nicotine concentrations of 4 flight attendants and 5 passengers on four, 4 hour Air Canada transcontinental flights, 2 B-727s and 2 B767s
Drake *et al* (1990)[51]; n = 4; Japan; tobacco industry	16 (SD 17)	4.5 (SD 3.8)	Not performed	28%	1987 Philip Morris study on 3 B-747 international JAL smoking flights measured nicotine in all classes and zones. Based on Repace analysis of data presented. Data as reported were lower, with average levels of nicotine in the smoking and non-smoking sections being 11 μg/m^3 (SD NR) and 2.5 μg/m^3 (SD NR) respectively.
Eatough *et al* (1992)[32]; n = 4; unknown; tobacco industry	41 (SD 26)	9.3 (SD 15)	Not performed	23%	Tobacco industry funded controlled experiment on four. 5 hour DC-10 smoking flights (airline not reported) at an air exchange rate of 30/hour, with zero recirculation of air. Data shown based on Repace analysis of data presented
Waters *et al* (2002)[23]; n = 6; USA; government	Not given	0.38–24 (range)	Not given	–	NIOSH study on 36 US domestic and international flights. Gate-to-gate times varied from 42 to 863 minutes, and passenger occupancy in coach from 34% to 100% of capacity

*Smoking-non-smoking border seats included; †calculated from data; ‡GM = geometric mean reported.
All means are arithmetic with standard deviation, unless identified as geometric means as reported.

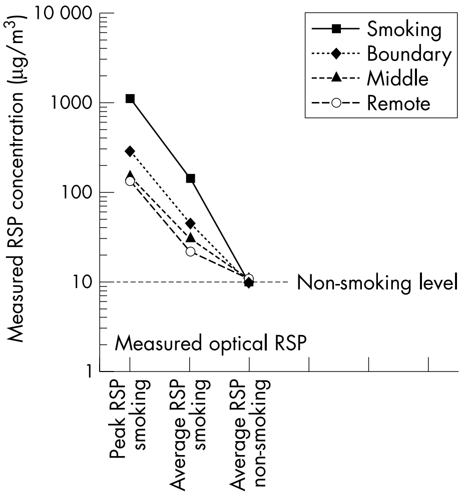

Figure 1 Measured RSP concentrations on eight international flights by seat location (Nagda *et al*[3] table 5-2; table 4–22). "Smoking" refers to seats in the smoking section, while "Boundary", "Middle", and "Remote" refer to seats in the non-smoking section, and describe their proximity to the smoking section. The dotted line indicates the RSP level on non-smoking flights.

relative humidity, CO_2, and temperature) on six B-767-300 intercontinental flights during nine smoking and eight non-smoking flights (190 seats, 50% recirculated air; cabin pressure 2000–2500 m; cabin volume 428 m^3).[24] A control group of 218 office workers was used for comparison. Cabin humidity was very low (5%), and CO_2 levels were below 1000 ppm. Annoyance from SHS was common among all aircrew work categories in the cabin (20–43%) but uncommon on the flight deck (4%) and in the office (8%). Effects were more common among atopic and younger crew. Lindgren *et al*[24] concluded that tobacco smoking onboard leads to significant respirable particle pollution. Lindgren and Norbäck[25] studied RSP in the aft galley area on 26 intercontinental flights of a B767-300 with and without tobacco smoking. They concluded that, despite the high air exchange rate and efficient air filtration on these flights, smoking in commercial aircraft leads to significant pollution and should be prohibited.[25]

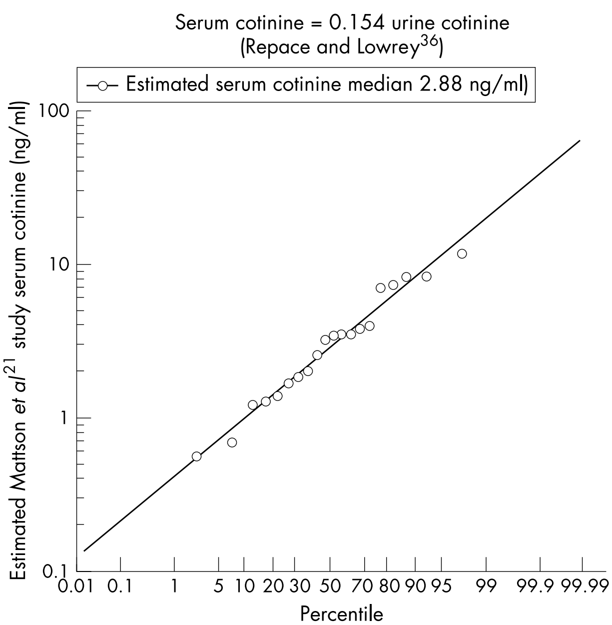

Figure 2 Log probability plot of the serum cotinine 12 hour post-exposure for the nine subjects on the Mattson *et al*[21] study, estimated from the creatinine normalised urinary cotinine (ng/ml) for subjects reporting no inter-flight SHS exposure (adapted from an analysis of fig 2 in Mattson *et al*[21]).

A Cathay Pacific Airways study conducted in 1996–97 by Lee *et al*[15] measured RSP by nephelometry on 16 flights of three wide bodied aircraft operating out of Hong Kong: the Boeing 747-400, Airbus-330, and Airbus-340. For three smoking flights, load factors were 60%, 60%, and 91%. The authors observed that there were major differences in the SHS concentration measured on smoking and non-smoking flights in the same cabin location.

NGO STUDY

In a study sponsored by ASHRAE, air quality was assessed on eight US carrier non-smoking flights on a B777-200 seating 305 to 320 passengers in July 1998, four each, domestic and international.[18 27] The outside air ventilation rate was 10 ft^3/min per person; HEPA-filtered air was recirculated at a rate of 10 ft^3/min per person. The mean CO_2 level in the aft galley and economy class respectively with recirculation on was 2840 parts per million (ppm), and 1405 ppm, and with recirculation off, 1350 ppm and 798 ppm. The report concluded that CO_2 levels averaged about 50% higher than recommended[28 29] by ASHRAE for public buildings. Insofar as perceptions of air quality, 3.2% of the passengers but 17.7% of the flight attendants rated air quality as "poor or very poor". Flight attendants' three top complaints were skin dryness or irritation, dry or stuffy nose, and dry itchy or irritated eyes. The report[18] concluded that RSP levels on these non-smoking flights were "very low" compared to other indoor environments. RSP levels (0.1–10 μm) were measured by continuous reading optical nephelometry with the level of detection being 10 μg/m^3. All readings were below the level of detection.

TOBACCO INDUSTRY STUDIES

The tobacco industry has taken a major interest in the issue of smoking on aircraft. In 1987, Oldaker & Conrad,[30] in an RJ Reynolds Tobacco Company study, measured gas phase nicotine on three narrow bodied B727-200, B737-200, and B737-300 aircraft. They concluded that average exposures in the non-smoking section were "insignificant compared to smoking a single cigarette", and that the aircraft ventilation systems were primarily responsible. A second tobacco industry funded study in 1988 by Malmfors *et al*[31] measured RSP and nicotine on 48 SAS DC-9 and MD-80 flights. The authors concluded that exposure to SHS on aircraft "is insignificant compared to total life exposure to indoor air pollutants" and that "an effective ventilation system is essential for cabin air quality". A third Philip Morris tobacco company funded study by Drake and Johnson,[51] undertaken in 1987 on four B-747 international JAL smoking flights, measured RSP and nicotine in all classes and zones. Drake and Johnson[51] concluded that "the 747's five air conditioning zones are reasonably effective in keeping SHS within the respective zones, and discharging it with relatively little entry into non-smoking areas".

A fourth study funded by the tobacco industry in 1992 investigated the variability of SHS tracers in a controlled experiment conducted on four, 5 hour DC-10 smoking flights (airline not reported) at a rate of 30 air changes per hour, with zero recirculation of air. Eatough *et al*[32] reported that SHS pollutants penetrating into the non-smoking section decay exponentially, with nicotine decaying faster than other species, and that additional data were needed to determine what variables control the rate of penetration. Eatough *et al* concluded that while the concentration of most SHS constituents can be calculated from the frequency of smoking, the size of the smoking section, and the ventilation rate, neither RSP nor nicotine could be accurately predicted by modelling. In 1991, a fifth publication by Crawford and Holcomb,[33] who did not advise that they were tobacco industry consultants, concluded in a review that "the very low levels of ETS in airliners do not appear to pose a measurable risk to health of passengers or flight attendants". Crawford asserted earlier[34] that high ventilation rates on aircraft "effectively control all pollutions"; Holcomb earlier claimed[35] that SHS is unfairly blamed for discomfort "due to its visibility".

NCI FLIGHT ATTENDANT DOSIMETRY STUDIES

The foregoing air quality monitoring studies are not measures of the actual SHS dose received by flight attendants, because area monitors do not reflect absorbed dose. Flight attendants' SHS dose was measured by cotinine dosimetry in an important study sponsored by the National Cancer Institute (NCI). Mattson *et al*[21] measured cabin air nicotine exposure and urinary cotinine dose in four flight attendants and five passengers on two international (San Francisco to Toronto and back) and two transcontinental (Toronto to Vancouver) smoking flights on Air Canada in May 1988. All subjects were non-smokers with no regular exposure to smoke, and were free of respiratory disorders. The first two flights were on B-727 narrow body jets with 100% fresh air. The latter two flights were on B-767 wide bodies, with 50% of the air recirculated. The same subjects were monitored in all flights (five passengers who sat in the smoking section or on its border, and four flight attendants who rotated assignments to smoking for half the flights and to non-smoking for the other half). Seventy two to 96 hours elapsed between flights. Air nicotine exposure via personal monitoring pumps and filters was assessed during the flight. Cigarettes were counted at intervals during the flights, and the extent and duration of between flight exposure to SHS was monitored by passive monitors and recorded in diaries.

Urinary cotinine excretion (normalised for creatinine) was sampled pre-flight and post-flight cotinine was collected over the 72 hour period following the flight. Subjects collected all their urine for each of 12, 6 hour periods post-flight. All subjects were non-smokers with no regular exposure to tobacco smoke, had their between flight exposure monitored with both a diary and passive nicotine monitor, and had pre-boarding baseline urine samples in addition to the 72 hour post-exposure urine collection. Significant differences in cotinine levels were observed over a 72 hour period between in-flight high nicotine exposures and low ones (that is, less than the median value). Mattson *et al*[21] correlated natural logarithms of nicotine and 12 hour post-exposure cotinine for subjects not re-exposed between flights ($R^2 = 0.74$, $p = 0.0003$).

Analysis of the nicotine data presented shows that personal nicotine monitors for the four attendants registered levels averaging 4.7 $\mu g/m^3$ (SD 4.0) while the five passengers averaged 15 $\mu g/m^3$ (SD 20) with an average of about $n_s = 4$ active smokers (SD 0.2) in four smoking rows during the smoking portion of the flights. Four active smokers is equivalent[9] to 12 habitual smokers, or about 9–12% of total passengers. Mattson *et al* reported that attendants worked in both smoking and non-smoking areas when they were assigned to the smoking area. Some non-smoking areas on board the aircraft had levels comparable to those in smoking sections. Exposure of attendants assigned to work in smoking was not significantly different from that of attendants who worked in non-smoking. Exposure among attendants was reported not statistically different from that of passengers, although none of the eight high nicotine exposures observed on the flights occurred among attendants.[21]

URINE AND SERUM COTININE FOR THE AIR CANADA FLIGHT ATTENDANTS

Repace *et al*[36 37] developed pharmacokinetic models from which cotinine in blood, urine, and saliva can be compared. These models accurately predicted levels found in observational studies of cotinine dose levels in non-smoking office workers and other cohorts. For example, Repace *et al*[37] estimated the median salivary cotinine dose of a typical office worker in an office with a 29% smoking prevalence and ventilated according to ASHRAE Standard 62–1989, as S = 0.5 ng/ml; this was the same as the observed median of 0.5 ng/ml measured in 89 office workers; the corresponding estimated serum cotinine equivalent is P = S/1.16 = 0.43 ng/ml, close to that measured in the NHANES III survey discussed below.

The anti-logarithms of Mattson *et al*'s[21] urine cotinine data are calculated and presented de novo in table 4, column 1; data for attendants and passengers with interflight exposure is excluded. The Air Canada flight attendant urine cotinine dose from table 4 may be converted into its serum cotinine equivalent using the urinary cotinine (U, ng/ml) to serum cotinine (P, ng/ml) conversion equation[36 37]: P = U/6.5 = 0.154 U (equation 1).

Using equation 1, the range of estimated serum cotinine for the Air Canada study flight attendants is about a factor of 20, from P = 0.55 to 11.54 ng/ml, with a median value of $P_{med} = (0.154)(18.72) = 2.88$ ng/ml (fig 2).

These urinary cotinine doses may be put into perspective by comparing their measures of central tendency to those of a national probability sample of cotinine collected by the Centers for Disease Control (CDC). Figure 3 compares the median for the subjects in the Mattson study[21] to the serum cotinine distribution for the NHANES III probability sample of all US adults exposed either at work or at home during 1988–1991.[38] The average US adult had a geometric mean dose of 0.205 ng/ml.[38] (For an ideal log normal distribution, the median and geometric mean are the same.[40]) This is more than seven times the US population (1988 to 1991) median serum cotinine value for non-smoking workers reporting exposure to SHS only at work from the NHANES III study (D Mannino, personal communication, US Centers for Disease Control, 1999) of $P_{US\ med.} = 0.393$ ng/ml. This is close to the geometric mean for the same worker group as reported[38] for the probability sample for the US population of workers exposed to SHS at work alone: $P_{US\ g.m.} = 0.468$ ng/ml. This is summarised in table 5. Moreover, table 4 and fig 3 show that 100% of the serum cotinine doses estimated from the measurements in the Mattson study during May 1988 exceeded those of the average US worker in CDC's NHANES III contemporaneous study measured during 1988–1991, indicating that the Air Canada flight attendants have been exposed to SHS at much greater levels than the average US worker.

GENERALISATION OF THE AIR CANADA STUDY

How do the Air Canada B-727s and 767s compare to others in service? Table 6 gives the nominal cabin volumes, extent of air recirculation, and air exchange rates for one narrow body and five wide body types.[3] All aircraft have a very low volume per person. How does this airspace compare with that afforded office workers? By comparison, a typical office has an occupancy of seven persons per thousand square feet, and for a 10 foot ceiling, an occupancy of seven persons per 10 000 ft^3 or per 283 m^3, yielding a space volume of 40.4 m^3 per person.[39] Thus, a typical office worker has (40.4/1.5) 27 times more airspace per occupant than a typical flight

Table 4 Urinary cotinine for four flight attendants and five passengers not re-exposed to SHS between flights: on four Air Canada flights, two B727s and two B767s, analysed from data presented in fig 2, in Mattson *et al*,[21] with serum cotinine estimated from Repace and Lowrey's[36] pharmacokinetic model: P = 0.154 U

	Measured 12 hour post-flight creatinine normalised cotinine (ng/ml-mgCr)	Estimated 12 hour post-flight serum cotinine (ng/ml)
	74.94	11.540
	53.60	8.2500
	53.60	8.2500
	47.42	7.3000
	45.06	6.9400
	25.58	3.9400
	24.43	3.7600
	22.81	3.5100
	22.57	3.4800
	22.10	3.4000
	20.98	3.2300
	16.46	2.5400
	13.01	2.0000
	11.94	1.8400
	10.70	1.6500
	8.87	1.3700
	8.21	1.2600
	7.85	1.2100
	4.47	0.69000
	3.57	0.55000
Mean (SD)	24.91 (19.71)	3.84 (3.04)
Median	18.72	2.88

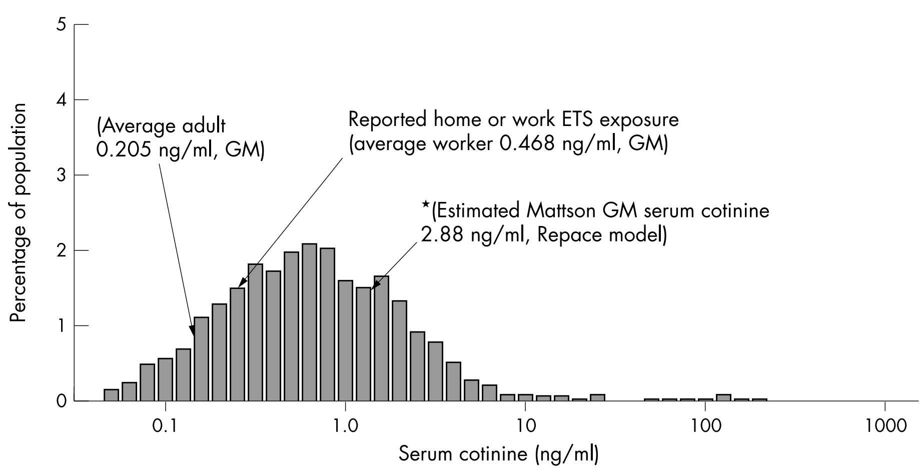

Figure 3 NHANES III distribution of cotinine in the US population versus the Mattson study. The median serum cotinine equivalent to the urinary cotinine level of 18.72 ng/ml is 2.88 ng/ml, which is six times the geometric mean (GM) serum cotinine level of the average US worker and 14 times that of the average adult, demonstrating that flight attendants have had abnormally heavy SHS exposure. NHANES III cotinine data from Pirkle *et al*.[38] *Repace *et al*.[36 37]

attendant. An aircraft cabin at 100% load factor has a 4–10 litres/s per person ventilation rate, compared to an office rate 10 litres/s per person. The aircraft person density[7] in the smoking section, 168 persons per 1000 ft^2, is greater than the 150 persons per 1000 ft^2 in a stand up bar with a ventilation rate of 15–25 litres/s per person,[28] or the 100 persons per 1000 ft^2 for an ordinary bar, at 15 litres/s per person,[39] and is much greater than the 70 persons per 1000 ft^2 for a smoking lounge ventilated at 30 litres/s per person.[29] Assuming a 10 ft ceiling, the smoking lounge has 4 m^3 per smoker, twice that of the aircraft, and has more than triple the ventilation rate, while the stand-up bar has 1.9 m^3 per person; if half of those persons are smokers, this is also about 4 m^3 per smoker, with 2–5 times the aircraft ventilation rate.

Although limited in number of subjects exposed in flight, the cotinine studies suggest that SHS exposure of flight

Table 5 Comparison of aircraft SHS dose with ground based dose for workers

Cotinine study; number of workers	Median serum cotinine level (ng/ml)	Exposure venue	Estimated ratio to average worker
Mattson *et al* [21]; n = 9	2.88*	Exposed on aircraft	6.1–7.3
NHANES III, Mannino (personal communication)	0.393	US workers, national sample	1.0
NHANES III, Pirkle *et al* [38]; n = 12000	0.468†	US workers, national sample	1.0

*Estimated from model; †geometric mean.

Table 6 Cabin volumes, percentage air recirculation, and air exchange rates[1 3 11]

Body type (W, wide; N, narrow)	Cabin volume (m^3)	% Air recirculation	Air exchange rate (/h)	Estimated average seating*	Volume per person (m^3)	Ventilation rate per person (litre/s)
Boeing 727-200^N	165	0	26.4	120	1.4	6–8
Boeing 747^W	790	26	14.7	452	1.7	7–10
Boeing 767-200^W	319	52	10.4	250	1.3	4
MD DC10-10^W	419	0	22.8	280	1.5	7–9
MD DC10-40^W	419	35	14.9	310	1.4	5
Airbus A-310^W	334		9.7	250	1.3	4

The B-747 has a passenger capacity of 331–550 persons, and the DC-10 from 250–380 persons.[1]
*At 100% load factor.[3]

attendants in general has been much greater than for average workers in ground based microenvironments. As discussed, the aircraft cabin has much less ventilation per person and much less space per person than offices, bars or smoking lounges. The latter is important because proximity to a pollution source increases exposure[42 43]—flight attendants have been exposed to tobacco smoke of passengers at distances approaching 0.5 m. The RSP and nicotine concentrations reported in tables 1–3 are measured by area monitors remote from the flight attendants' breathing zone, where they encounter more concentrated cigarette plumes as they serve smoking passengers. Area monitors cannot reflect flight attendants' respiration rates as they work or their mobility in the cabin. In other words, the SHS concentration in the breathing zone of a flight attendant *may be significantly underestimated* by the stationary area monitors which have been used in nearly all studies of SHS on aircraft. The best evidence of flight attendants' true exposure to SHS is therefore derived from cotinine dosimetry. Dosimetry, which incorporates proximity, duration, and respiration rate, is the gold standard in exposure assessment.[37]

DISCUSSION

Based upon stationary air monitoring studies in ~250 flights, levels of SHS-RSP are considerably higher on smoking flights than non-smoking flights, as summarised in tables 1 and 2. Based on these data, it appears that ~94% of the RSP pollution in the smoking section on aircraft is due to smoking. On a weighted mean basis, about 95% of the smoking section pollution, 160 μg/m^3, is from SHS. Similarly, when the weighted arithmetic mean of four studies of RSP in non-smoking sections on smoking flights (n = 125), 59 μg/m^3, is compared to that of the five studies of RSP on non-smoking flights (n = 59), 8 μg/m^3 (SD 3.3), most, (51/59) (100%) or 86% of the RSP in aircraft cabin non-smoking sections on smoking flights is estimated to come from SHS. This is supported by the nicotine studies in table 3 which show significant nicotine contamination in both smoking and non-smoking sections of aircraft on smoking flights, and the virtual absence of nicotine on non-smoking flights, and generalised by the models for SHS-RSP reported in table 3. It is evident that established aircraft ventilation rates and smoking rates *must* result in SHS-RSP levels of the order of several hundred micrograms per cubic meter.

Many epidemiological studies have shown that increases in daily average RSP levels are associated with increased morbidity and mortality.[44] The current US federal standard for $PM_{2.5}$ is 15 μg/m^3, annual average. In 1980, the annual federal standard for TSP was five times higher, at 75 μg/m^3. Repace and Lowrey[9] observed that a flight attendant working 40 hours per week would violate the (now obsolete) TSP standard by a factor of 1.2. Scaling this to the new $PM_{2.5}$ standard and a more realistic 20 hour flight attendant workweek,[8] yields a (1.2)(75/15)(20/40) = 3-fold violation of the $PM_{2.5}$ standard. This standard is designed to protect against such fine particle health effects as: premature death, increased emergency room visits and hospital admissions, increased respiratory symptoms and disease, decreased lung function, and alterations in lung tissue and structure and in respiratory tract defence mechanisms.[45]

In addition, SHS is a well established sensory irritant, variously producing itching, tearing, burning, swelling of eyes, sneezing, blocking, running, itching of nose, headache, cough, wheezing, sore throat, nausea and dizziness, and respiratory discomfort.[4 5 10 53 54] A recent Swiss study by Junker *et al*[46] reported an odour acceptability threshold of 1 μg/m^3 SHS-RSP, and a SHS-RSP irritation threshold level of 4.4 μg/m^3 SHS-RSP, compared to an RJ Reynolds tobacco company study,[47] which reported a SHS-RSP sensory (eye, nose, and throat) irritation threshold level of 58 μg/m^3. At that 4.4 μg/m^3 SHS-RSP level, only 33% of non-smoking test subjects found the air quality acceptable. The smoking section SHS-RSP level of 160 μg/m^3 of table 1 is nearly triple the RJ Reynolds study's irritation threshold. This SHS-RSP pollution level is also 36 times the Swiss study's eye, nose, and throat irritation threshold, and peak SHS-RSP pollution levels are sixfold higher than the mean, as illustrated in fig 1. The Swiss study[46] threshold will be used in this work.

Work related studies of SAS flight attendants during the late 1980s showed that two thirds of flight attendants surveyed reported suffering discomfort "to a great extent" from tobacco smoke.[7] In the words of one US flight attendant: "It was impossible to avoid tobacco smoke exposure no matter where I worked on the planes: although the areas that were designated smoking were…more concentrated, …the whole cabin reeked of smoke. You could smell and see it throughout the entire cabin". "You just couldn't avoid it. It was always worse on an airplane than in restaurants or bars, because there you could move or leave."[41] In the words of another: "Nonsmoking flight attendants were frequently asked by their doctors how long they'd been smoking…dentists would remove tobacco stains from their teeth,…burning eyes and bloody nostrils were considered normal…you lived with a dull headache, nasal burning and lowered energy…".[55] Anecdotes of this nature and more poignant ones were expressed by the flight attendant panel at the 1989 Congressional hearing. In the opinion of this observer, who testified at that hearing as a member of the federal panel, it was precisely such tales of suffering that gave life to the scientific data, and moved the Aviation Subcommittee to pass the six hour airline smoking ban. The second attendant further related: "In the years since SHS has been banned on aircraft, many of us have had a profound improvement in our symptoms…"[55]

In summary, the studies of airliner cabin air quality showed that tobacco smoke was a significant source of air pollution in aircraft cabins, that this tobacco smoke was absorbed by flight attendants and passengers, and that ventilation, the only available tool to limit SHS exposure on aircraft other than a smoking ban, was declining precipitously because of economic forces. All studies of SHS on aircraft yielded similar results; those sponsored by government, airlines, the tobacco industry, and NGOs. By the mid-1980s, SHS had been identified by both the NAS and the Surgeon General as a carcinogen and respiratory toxin as well as a major irritant.[1 4 5] The limitations on ventilation were emphasised by the chair of the ASHRAE 62 Ventilation Standard Committee in 1989: ''Dilution of tobacco smoke with outdoor air is an imperfect control mechanism. It depends not only on the amount of dilution air, but on the degree of mixing achieved, convection currents, electrical space charge effects, and perhaps other factors. *Therefore elimination of health risk through increased ventilation alone may not be possible*''[48] [emphasis added]. By contrast, the tobacco industry declaimed from the highest corporate levels that airline smoking bans were unjustifiable,[49] that SHS levels in airline cabins were ''miniscule'', and that adequate ventilation addressed poor air quality,[50] even after the Environmental Protection Agency[10] and others[53] had estimated thousands of US deaths annually from SHS.

CONCLUSIONS

- Flight attendants were exposed to elevated levels of fine particle pollution (RSP) on aircraft for many decades. After smoking was no longer permitted on aircraft, about 95% of the RSP in the smoking sections of the aircraft cabin and 85% of the pollution in the non-smoking sections disappeared, relieving a substantial air pollution burden.
- Comparison of the SHS dose levels measured in a small but well done study of flight attendants with those measured in a national probability sample of the US population suggests that flight attendants had about 6 to 7 times the SHS exposure of typical ground based workers, and 14 times that of the typical person.
- Studies of SHS contaminants on aircraft funded by the government, the airlines, non-governmental organisations, and the tobacco industry yielded similar concentrations. However, while the government and airline studies concluded that SHS caused an air pollution problem for passengers and crew, the tobacco industry asserted that SHS was adequately controlled by ventilation systems, and aggressively opposed smoking bans.
- The area, volume, and ventilation rate per smoker on aircraft is the smallest of any social setting, including stand-up bars and smoking lounges.
- While US smoking prevalence declined by 22% from 1970 to 1987, aircraft smoking prevalence declined by only 13%. However, cabin ventilation rates declined by 33–60%, during the same period. Thus, aircraft air exchange rates dropped about three times faster than aircraft smoking prevalence.
- Measurements of contaminants in both smoking and non-smoking sections compared to personal monitoring of flight attendants indicate that separation of the cabin into smoking and non-smoking sections did not significantly reduce flight attendants' exposure to SHS, due to their mobility.
- A study of flight attendants during the late 1980s showed that two thirds complained of suffering ''to a great extent'' from secondhand smoke exposure. Typical levels of SHS-RSP found in smoking sections of aircraft are found to have violated current federal air quality standards by an estimated threefold, and exceeded threshold levels for SHS irritation by one to two orders of magnitude.
- These results have implications for studies of the past and future health of flight attendants.

What this paper adds

For years, passengers and cabin crew repeatedly complained about poor air quality in aircraft cabins caused by secondhand smoke (SHS). In 1973, in response to passengers' complaints, the US Civil Aeronautics Board established non-smoking sections in passenger aircraft cabins, creating zones of higher and lower SHS pollution. However, it remained until 1989 for the US Congress to ban smoking on flights up to six hours duration, largely to protect cabin crew. Smoking bans subsequently spread internationally. However, many longer duration international flights remained polluted with tobacco smoke until the final years of the 20th century. Despite decades of complaints, air quality and dosimetry data on flight attendants' exposures to SHS have been measured on only a relatively small number of flights. These data were interpreted by government, non-governmental organisations, and airlines to support the need for smoking bans to control SHS pollution in aircraft cabins, and by the tobacco industry to support the contention that ventilation systems controlled SHS, obviating the need for smoking bans.

Using information on aircraft ventilation rates and smoker densities, coupled with air quality data collected before and after the aircraft smoking ban, this paper generalises measurements of atmospheric markers for SHS in aircraft cabins and biomarkers for SHS exposure in flight attendants into a new perspective. It shows that aircraft ventilation systems were incapable of controlling SHS, such that nearly all of the harmful SHS respirable particulate (RSP) air pollution in both the smoking *and* non-smoking sections of aircraft cabins was from SHS. It appears that 21st century health based federal air quality standards for RSP were seriously compromised for flight attendants in aircraft cabins during the 20th century smoking era, and that SHS-RSP levels massively exceeded recently measured SHS irritation thresholds. Further, flight attendant dosimetry indicates that workplace SHS exposures in aircraft cabins were far greater than for typical non-smokers in the general population. This has implications for studies of the impact of flight attendants' workplace SHS exposures on their past and future health.

ACKNOWLEDGEMENTS

The author is grateful to the Flight Attendant Medical Research Institute for support of this work, and thanks NL Nagda, WR Ott, LA Wallace, and MA Waters for helpful discussions.

The author testified before the House Subcommittee on Aviation on the risks from SHS to flight attendants in 1989, served as an advisor to the US Department of Transportation's Airline Cabin Air Quality Study in 1988, and since 1998, has served as an expert witness for the plaintiffs in litigation involving flight attendants, airlines, and the tobacco industry.

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