

AEROTOXIC SYNDROME: ADVERSE HEALTH EFFECTS FOLLOWING EXPOSURE TO JET OIL MIST DURING COMMERCIAL FLIGHTS

Chris Winder
School of Safety Science
University of New South Wales
Sydney NSW 2052,
Australia

Jean-Christophe Balouet
Environnement International
31 Rue du Général Chanzy
94130 Nogent sur Marne
France

Abstract

Materials used in the operation of aircraft may contain hazardous ingredients, some with significant toxicities, and need care in handling and use. Some maintenance or operational activities, such as leaks or poorly controlled maintenance procedures, can, through contamination of aircraft cabin air, produce unwanted exposures to personnel and passengers. Occasionally, such exposures (either short term intense or long term low level) may be of a magnitude to induce symptoms of toxicity. The symptoms reported by exposed individuals are sufficiently consistent to indicate the possibility of a discrete occupational health condition, termed aerotoxic syndrome. Features of this syndrome are that it is associated with air crew exposure at altitude to atmospheric contaminants from engine oil or other aircraft fluids, chronologically juxtaposed by the development of a consistent symptomatology of irritancy, sensitivity and neurotoxicity. This syndrome may be reversible following brief exposures, but features are emerging of a chronic syndrome following moderate to substantial exposures.

Introduction

Aircraft materials such as jet-fuel, de-icing fluids, engine oil, hydraulic fluids, and so on, contain a range of ingredients, some of which can be toxic. Although these chemicals are usually retained in engines and equipment into which they have been added, they can sometimes find their way into cabin air where crew and passengers are located, through incidents such as engine oil leaks, seal failures and fluid ingestion by APU/engines. Further, operational activities, such as APU "pack" burn outs, can give rise to significant contamination.

Dozens of in-cabin leak/smoke events are documented annually, often correlated to aircraft fluid leak events. Fume events are much more frequent, correlated to less important aircraft fluid leaks (hundreds per year), or to other independent sources. In total, aircraft fluid leak/fume/smoke events are estimated to impact over 300 flights per year worldwide, resulting in exposures to an estimated 40,000 or more crew and passengers. Some models of airplanes appear to be particularly prone to leaks.

The range of bleed air contaminants and their concentrations, which may be found during in-cabin contamination events during flight, can be extensive. Significant contaminants include: carbon monoxide, aldehydes; aromatic hydrocarbons; aliphatic hydrocarbons; chlorinated, fluorinated, methylated, phosphate, nitrogen compounds; esters; and oxides. One additional problem is the lower oxygen concentration operating in the cabins of planes flying at altitude.

Inhalation is an important route of exposure, with exposure to uncovered skin being a second, less significant route (for example, following exposure to oil mists) and ingestion improbable.

In terms of toxicity, a growing number of crew are developing symptoms following both short term and long term repeated exposures. Neurotoxicity is a major flight safety concern, especially where exposures are intense.

Symptoms

Symptoms have been collected from ten cases of pilots, first officers, pursers and flight attendants, flying in five airlines, three models of airplane and in four countries. The only common feature is that at some stage, they were involved in an incident where a leak of oil mist to the flight deck or passenger cabin occurred.

Symptoms were reported from single exposures to elevated exposures, and from long term low level exposures to low level oil leaks or residual problems from previous contamination. Combined exposures (that is, short term intense exposures combined with low level long term exposures) were also prevalent.

Symptoms from single or short term exposures are shown in Table 1 below and include: blurred or tunnel vision, disorientation, memory impairment, shaking and tremors, nausea/vomiting, parasthesias, loss of balance and vertigo, seizures, loss of consciousness, headache, lightheadedness, dizziness, confusion and feeling intoxicated, breathing difficulties (shortness of breath, tightness in chest, respiratory failure), increased heart rate and palpitations, nystagmus, irritation (eyes, nose and upper airways).

Table 1: Aerotoxic Syndrome – Symptoms, Intensity and Chronological Sequence

Symptom	Imme- diate	Post- flight	Short term	Medium term	Long term
Seizures, "gray outs", unconsciousness	✓✓	✓			
Disorientation	✓✓	✓✓	✓		
Loss of balance	✓✓	✓✓	✓	✓	
Problems with coordination	✓✓	✓✓	✓✓	✓	
Headache, lightheaded, dizziness	✓✓	✓✓	✓✓	✓✓	✓✓
Weakness, fatigue, exhaustion	✓✓	✓	✓	✓	✓
Chronic fatigue			✓	✓✓	✓✓
Cognitive problems	✓	✓	✓✓	✓✓	✓✓
Numbness, hot flashes	✓✓	✓✓	✓	✓	
Shaking/tremors, fasciculations, nystagmus	✓✓	✓✓	✓	✓	✓
Irritation of eyes, nose and throat	✓✓	✓			
Nausea, vomiting	✓✓	✓✓			
Blurred vision, tunnel vision	✓✓	✓	✓		
Respiratory problems	✓✓	✓			
Chest pain	✓✓	✓			
Increased heart rate, palpitations	✓	✓			
Joint pain, muscle weakness, salivation	✓	✓			
Rashes, blisters (uncovered body parts)	✓	✓✓	✓		
Loosing hair (2 cases of severe exposure)		✓	✓		
Immunodepression			✓	✓	
Acquired Multiple Chemical Sensitivity				✓	✓✓

Key to Exposure Intensity:
 ✓ Mild intensity and/or symptoms occur occasionally
 ✓✓ Severe intensity and/or symptoms present continuously

Key to Column headings:
Immediate: minutes to hour, during or soon after exposure
Post-flight: hours to days
Medium term: weeks to months
Short term: days to weeks
Long term: months to years

Symptoms from long term low level exposure or residual symptoms from short term exposures include: memory impairment, forgetfulness, lack of coordination, nausea/vomiting, diarrhoea, respiratory problems, chest pain, severe headaches, dizziness and feeling intoxicated, weakness and fatigue (leading to chronic fatigue), exhaustion, increased heart rate and palpitations, numbness (fingers, lips, limbs), hot flashes, joint pain, muscle weakness and pain, salivation, irritation (eyes, nose and upper airways), skin itching and rashes, skin blisters (on uncovered body parts), signs of immunosuppression, hair loss, chemical sensitivity leading to acquired or multiple chemical sensitivity (see Table 1).

It is also apparent that some symptoms occur immediately or soon after exposure, for example, many of the irritant, gastric, nervous and respiratory effects. However, others, such as nervous system impairment, immunodepression and chemical sensitivity, develop later, perhaps months after exposures may have ceased. Further, while some of these symptoms are fully reversible, others appear to persist for longer (see Table 1). Debate is also continuing about the links between exposure and some of longer term symptoms (such as chemical sensitivity).

Symptom severity depends on a number of factors, including the range of contaminants present, the intensity, duration and frequency of exposure, toxicity of compounds (expectedly influenced by cabin environment factors such as humidity, decreased oxygen concentration and contaminants such as carbon monoxide), and individual

susceptibility.

While single/long term exposure to aircraft engine lubricants and hydraulics (basically due to their chemical content and possible thermal decomposition products) is diagnosed as responsible for the aerotoxic syndrome, air crew or passengers exposed to same events or similar doses do not necessarily develop same symptom severity. The variation in symptoms severity is attributed to individual susceptibility, including anaphylactic response, may also depend on other potentiation factors, including prior exposure events.

Aerotoxic Syndrome

The symptoms reported by exposed individuals as shown in Table 1 are sufficiently consistent to indicate the development of a discrete occupational health condition, and the term aerotoxic syndrome is introduced to describe it. Features of this syndrome are that it is associated with air crew exposure at altitude to atmospheric contaminants from engine oil or other aircraft fluids, chronologically juxtaposed by the development of a consistent symptomology of irritancy, sensitivity and neurotoxicity. This syndrome may be reversible following brief exposures, but features are emerging of a chronic syndrome following significant exposures.

Management of Occupational Health and safety in the Aviation Industry

It has become apparent that the primary safety consideration of the airlines is to keep airplanes flying - the safety of workers appears to have a very low priority to operational safety. Further, the regulatory agency involved in aviation safety (the Civil Aviation Safety Authority) admitted in evidence to the Senate Aviation Inquiry that its area of responsibility is airplane safety, not occupational health and safety.

Monitoring studies conducted by aircraft manufacturers and the airlines have failed to detect any major contaminants, although to date most monitoring studies have used inappropriate sampling techniques (such as air collection of poorly volatile contaminants) or inadequate methodologies (such as sample collection time, sample volume, storage of samples, not taking account of altitude). No monitoring has been conducted during a leak incident

Attempts by airlines to address this problem through design, maintenance and operational improvements and through staff support and medical care have not been successful, and in the main, continue to be reactive and piecemeal. Obviously, in some cases, options such as improving engine design are not within the sphere of activity of the operators. The efficacy of recent modifications to the aircraft remains unknown, and leaks are still occurring, albeit at a reduced rate.

An admission was grudgingly made by one airline in 1998 that adverse exposures had been occurring, and that such exposures might cause irritation and transient effects. However, the development of long term symptoms is vigorously denied.

Civil aviation regulations clearly state that "the ventilation system must be designed to provide a sufficient amount of uncontaminated air to enable the crew members to perform their duties without undue discomfort or fatigue and to provide reasonable passenger comfort." The admission that irritation and transient symptoms can occur demonstrates non-compliance with the above rules.

Further, the adversarial and acrimonious manner in which some airlines have pursued workers compensation cases brought by staff with aerotoxic syndrome indicates a confrontational approach which is unlikely to be beneficial to all parties in the long term.

Conclusions

Direct exposure to hydraulics and lubricants are known to be toxic, causing effects such as blurred vision, disorientation, memory loss, lack of coordination, nausea, that if they occurred in flight crew, are direct threats to flight safety. Further, there is factual evidence that flight deck, cabin crew and passengers can be directly exposed to trace chemicals on aircraft in sufficient concentrations to cause acute, immediate to long term symptoms.

These exposures can produce symptoms of toxicity. Symptoms associated to the aerotoxic syndrome clearly include neurotoxicity as neuropsychological effects, as well as other symptoms typically correlated to chemical intoxication. Links between neurotoxic effects and certain contaminants known to be neurotoxic (such as the phosphate esters) are suspected.

Aerotoxic syndrome presents significant issues with regard to the health of pilots, cabin crew and passengers, but most notably with regard to air safety if pilots are incapacitated and cabin crew cannot supervise cabin evacuations during emergencies. Health effects include short term irritant, skin, gastrointestinal, respiratory and nervous system effects, and long term central nervous and immunological effects. Some of these effects are transient, others appear more permanent. The exacerbation of pre-existing health problems by toxic exposures is also highly probable.

This is a hidden issue. Staff of the airlines are worried about job security and what might happen to them if they complain about working conditions and make their symptoms public. At present, with only a few cases proceeding in the courts, little compensation has been awarded to airline workers affected by toxic fumes. Therefore, staff are reluctant to come forward until their health is jeopardised sufficiently that they can no longer fly without compromising their health and safety.

Aircrew Exposure to Chemicals in Aircraft: Symptoms of Irritation and Toxicity¹

Chris Winder² and Jean Christophe Balouet³

Keywords: Aerotoxic syndrome, irritation, toxicity, airborne chemicals, neurotoxicity, chemical safety, phosphate esters, case studies

Summary

Materials used in the operation of aircraft may contain hazardous ingredients, some with significant toxicities, and need care in handling and use. Some maintenance or operational activities, such as leaks or poorly controlled maintenance procedures, can, through contamination of aircraft cabin air, produce unwanted exposures to crew and passengers. Occasionally, such exposures (either short term intense or long term low level) may be of a magnitude to induce symptoms of toxicity.

These symptoms are associated with air crew exposure at altitude to atmospheric contaminants from engine oil or other aircraft fluids, temporally juxtaposed by the development of a consistent symptomology of short-term skin, gastro-intestinal, respiratory and nervous system effects, and long-term central nervous and immunological effects. Symptoms from seven case studies, from flight crew and flight attendants in four airlines operating in four countries and in three airplane models are listed. These symptoms may be reversible following brief exposures, but features are emerging of longer term problems following significant exposures. This has significant implications for safety in the aviation industry and occupational health.

Introduction

Chemical exposures in aircraft are not unheard of. Aircraft materials such as jet-fuel, de-icing fluids, engine oil, hydraulic fluids, and so on, contain a range of ingredients, some of which are toxic.^{1,2,3,4} In 1953, The Aeromedical Association first expressed their concerns about the toxicity risks of cabin air contamination by hydraulics and lubricants.⁵ Other risks have been identified more recently, either as part of the chemicals routinely used in maintaining airplanes,⁶ or as toxicological factors in aviation accidents⁷ There are a range of possible situations that can arise whereby airplane cabin air can be contaminated.⁸

The aviation industry has used engine oil, hydraulic fluids and other materials that can contain a range of toxic ingredients, for example:

- organophosphate compounds, including Tricresyl phosphates (TCP), Tributyl phosphates (TBP), Triphenyl phosphates (TPP) and their derivatives, from 3 to 25% in content;
- other toxic inorganic molecules, such as naphthylamines, amines and esters;

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² School of Safety Science, University of New South Wales, Sydney NSW 2052, Australia.

³ Environment Communication, 31 rue du Général Chanzy, 94130 Nogent, France.

- organometallic additives (zinc dialkyl dithiophosphates, calcium alkyl phenates, magnesium sulphonates, molybdenum and barium containing additives).

Some of these contamination problems can persist for decades. For example, a problem of oil contamination of the air conditioning system of the BAe 146 was first noted by the aircraft manufacturer in 1984,⁹ but was the subject of a specific term of reference to an Australian Senate Aviation Inquiry held 1999-2000, over fifteen years later.¹⁰ While changes in product formulations have attempted to make less toxic products,¹¹ concern still exists as to the potential toxicity that exposure to these materials may cause.¹²

Although these chemicals are usually retained in the engines and equipment into which they have been added (such as auxiliary pack units or APUs), they can sometimes find their way into cabin air where crew and passengers are located, through incidents such as engine oil leaks, seal failures and fluid ingestion by APU/engines.

Dozens of in-cabin leak/smoke events are documented annually (for example, through the NASA self reporting system, BASI, NTSB), often correlated to aircraft fluid leak events. Fume events are much more frequent, correlated to less important aircraft fluid leaks (hundreds per year), or to other independent sources (not statistically studied in this paper). In total, aircraft fluid leak/fume/smoke events are estimated to impact over 300 flights per year world-wide (statistically above 1 complaint flight out of 25,000 flights), resulting in exposures to an annually estimated 40,000 or more crew and passengers worldwide (a billion passengers in 1999).¹³ However, a figure of over one complaint flight out of 2500 flights is documented in at last three major airline companies.

Symptoms following Irritating and Toxic Exposures

Symptoms may be possible from single/short term or longer-term exposures.

The earliest case found in the literature was reported in 1977. A previously healthy member of an aircraft flight crew was acutely incapacitated during flight with neurological impairment and gastrointestinal distress. His clinical status returned to normal within a day. The etiology of his symptoms was related to an inhalation exposure to aerosolised or vaporised synthetic lubricating oil arising from a jet engine of his aircraft.¹⁴

Other studies of exposures in airplanes exist in the literature, including a 1983 study of eighty nine cases of smoke/fumes in the cockpit in the US Air Force,¹⁵ a study of 1983 study of Boeing 747 flight attendants in the USA,¹⁶ and a 1998 study of BAe 146 flight crews in Canada over a four-month period.¹⁷ There are common themes in symptom clusters in these studies, as shown in the table below.

Table 1: Studies reporting symptoms of irritancy and toxicity in aircrew

	Reference	15	16	17
	Number of cases/reports	89	248	112
○ watery eyes				6
○ eye irritation		31	74%	
○ burning eyes				27
○ blurred vision				1
○ loss of visual acuity		10	13%	
○ runny nose			43%	
○ sinus congestion		31	54%	6
○ dry painful nose			57%	
○ nose bleed			17%	

	Reference	15	16	17
Number of cases/reports		89	248	112
<input type="radio"/>	burning throat			48
<input type="radio"/>	throat irritation		64%	
<input type="radio"/>	gagging and coughing	2		3
<input type="radio"/>	cough dry		69	
<input type="radio"/>	cough wet		6%	
<input type="radio"/>	cough blood		2%	
<input type="radio"/>	shortness of breath		73%	
<input type="radio"/>	difficulty in breathing		68%	
<input type="radio"/>	pain on deep breathing	6	81%	
<input type="radio"/>	chest pains	6		7
<input type="radio"/>	increased heart rate		2%	
<input type="radio"/>	breathing problems requiring oxygen			2
<input type="radio"/>	loss of voice		35%	
<input type="radio"/>	headache	22	52%	29
<input type="radio"/>	dizziness/loss of balance	42		7
<input type="radio"/>	light-headedness	42		6
<input type="radio"/>	feeling faint		54%	
<input type="radio"/>	actually faint/loss of consciousness	4	4%	
<input type="radio"/>	trouble thinking or counting	23	39%	
<input type="radio"/>	disorientation	23		17
<input type="radio"/>	behaviour modified	23	20%	
<input type="radio"/>	feeling "spaced out"		36%	
<input type="radio"/>	tingling of nose and lips	8		3
<input type="radio"/>	numbness			2
<input type="radio"/>	muscle cramp		29%	
<input type="radio"/>	nausea	23	23%	9
<input type="radio"/>	abdominal spasms/vomiting	23		
<input type="radio"/>	change in urine		3%	

The range of symptoms in these studies is quite broad, affecting many body systems. In some cases, it is quite likely that symptoms in one study are similar to those in the others (for example, trouble in thinking and counting and cognitive problems).

A preponderance of the symptoms reported above are related to exposure to an irritant, (indeed, the earlier Tashkin study suggests ozone as a cause, even though a battery of pulmonary function tests failed to reveal abnormalities). However, the presence on symptoms related to central nervous system dysfunction, hair loss, muscular and gastrointestinal problems, suggests the possibility of a component of systemic toxicity.

The Case Studies

To study some of the problems of exposure to flight crew and flight attendants exposed to in cabin contamination while flying, seven cases of symptom development from such exposure events were investigated. These case studies were taken from flight crew and flight attendants in four airlines operating in four countries and in three airplane models. A wide range of symptoms is reported in these seven case studies. A summary of the effects seen in these seven case studies is shown in the table below.

Table 2: Symptom Summary: Seven Case Studies

Symptom/Symptom cluster	Case Study No							Tot
	1	2	3	4	5	6	7	
Loss of consciousness, "grey out"		✓		✓	✓			3
Ataxia, seizures				✓				1

Symptom/Symptom cluster	Case Study No							Tot
	1	2	3	4	5	6	7	
Narcosis, somnolence		✓	✓					2
Vertigo	✓	✓						2
Loss of balance	✓	✓			✓	✓		4
Disorientation	✓	✓	✓	✓				4
Shaking/tremors/tingling				✓	✓	✓		3
Numbness (fingers, lips, limbs), loss of sensation		✓			✓	✓	✓	4
Light-headed, dizziness, feeling of intoxication	✓	✓	✓	✓	✓	✓	✓	7
Severe headache, head pressure	✓	✓	✓	✓	✓	✓	✓	7
Memory loss, memory impairment, forgetfulness, confusion	✓	✓	✓	✓	✓	✓	✓	7
Coordination problems	✓	✓	✓	✓	✓	✓		6
Word blindness			✓					1
Sleep problems			✓		✓	✓		3
Irritability		✓	✓			✓	✓	4
Depression	✓	✓	✓					3
Nystagmus					✓			1
Irritation of eyes, nose and throat	✓	✓	✓	✓	✓	✓	✓	7
Eye pain, problems			✓	✓	✓	✓		4
Vision problems				✓	✓	✓	✓	4
Sinus problems			✓			✓		2
Respiratory distress, difficulty in breathing	✓			✓		✓	✓	4
Chest tightness	✓	✓		✓				3
Chest pain		✓		✓				2
Increased heart rate, palpitations	✓	✓		✓				3
Nausea, vomiting	✓	✓	✓		✓	✓	✓	6
Abdominal pain, cramps, diarrhoea	✓			✓	✓			3
Sweating				✓				1
Rashes, blisters (uncovered body parts)			✓	✓		✓	✓	4
Hair loss	✓			✓		✓		3
Joint pain, muscle weakness					✓		✓	2
Fatigue, exhaustion	✓	✓	✓	✓	✓	✓	✓	7
Chronic fatigue	✓		✓	✓		✓	✓	5
Metabolic difficulties			✓					1
Weight loss					✓			1
Swollen glands, glandular problems			✓		✓	✓		3
Dysmenorrhoea				✓				1
Thyroid problems	✓							1
Immunodepression			✓				✓	2
Food/alcohol intolerances			✓		✓	✓	✓	4
Multiple Chemical Sensitivity			✓		✓	✓	✓	4

The consistency between the symptoms between these individuals is, in many cases, quite remarkable. The comparison of symptoms between Tables 1 and 2 are also noteworthy. The term aerotoxic syndrome was proposed in 1999 to describe the association of symptoms observed amongst crew exposed to hydraulic or engine oil smoke/fumes.^{18,19}

An additional case which supports the problem of neurotoxicity in flight crew occurred in July 1997, when a pilot experienced difficulties (difficulty in concentration and loss of situational awareness) following the presence of strong oily odours and fumes in the cockpit while landing a plane, whereby the pilot had to hand over the plane to the first officer. This incident was subject of a report to the Australian Bureau of Air Safety.²⁰ One extract of this report is:

At 3,000 ft on approach to Melbourne Airport, the pilot suffered vertigo and handed control of the aircraft to the co-pilot. At the same time a check pilot suffered from

nausea. The incapacitation occurred after the crew smelt oil fumes in the cockpit air supply.

The onboard maintenance record noted that an oil smell had been reported 23 days prior to this incident, and that the repair had been noted for repair at company convenience, indicating even in 1997, the lack of priority that the airlines gave to oil fume problems. The consequences of what might have occurred if oil fumes had affected two of two pilots, rather than two of three pilots are unthinkable.

Further, it is possible to separate out short term and long term symptoms.

Symptoms from short term exposure

Symptoms from single or short-term exposures include:

- neurotoxic symptoms: blurred or tunnel vision, nystagmus, disorientation, shaking and tremors, loss of balance and vertigo, seizures, loss of consciousness, parathesias;
- neuropsychological symptoms: memory impairment, headache, light-headedness, dizziness, confusion and feeling intoxicated;
- gastro-intestinal symptoms: nausea, vomiting;
- respiratory symptoms: cough, breathing difficulties (shortness of breath), tightness in chest, respiratory failure requiring oxygen;
- cardiovascular symptoms: increased heart rate and palpitations;
- irritation of eyes, nose and upper airways.

Neurotoxicity is a major flight safety concern, especially where exposures are intense.

Symptoms from long term exposure

Symptoms from long term low-level exposure or residual symptoms from exposure events include:

- neurotoxic symptoms: numbness (fingers, lips, limbs), parathesias;
- neuropsychological symptoms: memory impairment, forgetfulness, lack of co-ordination, severe headaches, dizziness, sleep disorders;
- gastro-intestinal symptoms: salivation, nausea, vomiting, diarrhoea;
- respiratory symptoms: breathing difficulties (shortness of breath), tightness in chest, respiratory failure, susceptibility to upper respiratory tract infections;
- cardiovascular symptoms: chest pain, increased heart rate and palpitations;
- skin symptoms: skin itching and rashes, skin blisters (on uncovered body parts), hair loss;
- irritation of eyes, nose and upper airways;
- sensitivity: signs of immunosuppression, chemical sensitivity leading to acquired or multiple chemical sensitivity

- general: weakness and fatigue (leading to chronic fatigue), exhaustion, hot flashes, joint pain, muscle weakness and pain.

One last point should be noted. In a US NTSB 1983 study of problems of turbine oil by-product contamination, a statement appears which says:²¹

“there are certain instances in which chronic or repeated exposure may sensitize a person to certain chemicals so that later concentrations in the ppb range may later elicit an acute hypersensitivity type reaction.”

The number of cases now following exposure to irritating and toxic exposures in airline personnel suggest that a hypersensitivity reaction of this type may be occurring in an estimated 2 to 3% of the exposed. However, the intensity of the hypersensitivity reaction now occurring would suggest that it is not of a life threatening form.

Symptom duration

It is also apparent that some symptoms occur immediately or soon after exposure, for example, many of the irritant, gastric, nervous and respiratory effects. However, others, such as nervous system impairment, immunosuppression and chemical sensitivity, develop later, perhaps months after exposures may have ceased. Further, while some of these symptoms are fully reversible, others appear to persist for longer (in some of the longer cases, for at least five years). Debate is also continuing about the links between exposure and some of longer-term symptoms (such as chemical sensitivity).

Symptom severity

Symptom severity depends on a number of factors, including the range of contaminants present, the intensity, duration and frequency of exposure, toxicity of compounds (expectedly influenced by cabin environment factors such as humidity, decreased oxygen concentration and contaminants such as carbon monoxide), and individual susceptibility.

While single/long term exposure to aircraft engine lubricants and hydraulics (basically due to their chemical content and possible thermal decomposition products) is diagnosed as responsible for the reported symptoms, air crew or passengers exposed to same events or similar doses do not necessarily develop same symptom severity. Variation in symptom severity is attributed to individual sensitivity, and may also depend on other susceptibility factors, including prior exposure events.

In terms of toxicity, a large number of crew are developing symptoms^{16,17,22,23} following both short-term and long term repeated exposures. Neurotoxicity is a major flight safety concern,²⁴ especially where exposures can be intense.

Attempts by airlines to address this problem through design, maintenance and operational improvements and through staff support and medical care have not been successful, and in the main, continue to be reactive. Obviously, improving options such as engine design, using less toxic fluids, improved reporting systems, and better maintenance procedures are not within the sole sphere of activity of the operators. However, the manner in which some airlines have pursued workers compensation cases brought by staff with some of the longer term symptoms indicates a confrontational approach which is unlikely to be beneficial to all parties in the long-term.

Conclusions

Direct exposure to smoke/fumes from hydraulic fluids and lubricants are known to be toxic, causing effects such as blurred vision, disorientation, memory loss, lack of coordination, nausea, that if they occurred in flight crew, are direct threats to flight safety. Further, through documentation such as reports of cabin air contamination by engine oil and hydraulic fluids in engine logs and pilot reports, factual evidence is available that flight deck, cabin crew and passengers can be directly exposed to airborne chemicals on aircraft in sufficient concentrations to cause acute, immediate to long-term symptoms.

These exposures can and do produce symptoms of toxicity. Symptoms associated with cabin contamination clearly include irritancy, neurotoxicity and neuropsychological effects, as well as other symptoms typically correlated to chemical intoxication. Links between neurotoxic effects and certain contaminants known to be neurotoxic (such as the phosphate esters) are suspected.

These exposures, and the symptomology they produce, present significant issues with regard to the health of pilots, cabin crew and passengers, but most notably with regard to air safety if pilots are incapacitated and cabin crew cannot supervise cabin evacuations during emergencies. Health effects include short-term irritant, skin, gastro-intestinal, respiratory and nervous system effects, and long-term central nervous and immunological effects. Some of these effects are transient, others appear more permanent. The exacerbation of pre-existing health problems by toxic exposures is also highly probable.

Aviation has been a pioneering industry for decades. However, the industry is coming under increasing pressure to improve its standards. Public confidence in a traditionally safe, high technology industry, is eroding to the perception of a standpoint of "fly at any cost". Minimalist approaches to regulatory compliance, an almost total focus on profit making at the expense of other commercial priorities (such as safety or staff health), and strident denials that problems exist are not hidden do little to build confidence.^{25,26}

Human factors need to be considered too. Staff of the airlines are worried about job security and what might happen to them if they complain about working conditions and make their symptoms public. At present, with only a few dozen cases proceeding in the courts, little compensation has been awarded to airline workers affected by toxic fumes and several have already lost their jobs (for example: the pilot fired two months after incident in case study no 2; pilot in early retirement within one year after incident, early retirement by five years, in-flight engineer fired a few months after incident for "insubordination" in case study no 3; flying licence lost in case studies nos 5 and 7). Therefore, staff are reluctant to come forward until their health is jeopardised sufficiently that they can no longer fly without compromising their health and safety.

In one workers' compensation court proceedings in Australia, one airline has admitted that exposure events are significant enough to produce symptoms of irritation.²⁷ Debate about other effects, and about the significance of long term sequelae continues. The case was concluded as the exposures exacerbating a pre-existing medical condition.

The issue has generated considerable interest in the international community and various international programs are being started in the USA and Europe. This international dimension is of major importance since exposed and symptomatic crews have been identified in at least three continents, and all aircraft types have had leak problems.

APPENDIX 1: THE CASE STUDIES

CASE STUDY No 1

Demographic/occupational	Country:	France
Aircraft type:	B-747	Date of incident: 1985
Occupation:	Cabin crew	Years of experience: 15-20
Age at incident:	35-40	Gender: Female
Medical:	Asthma, non-smoker, no alcohol, no recent illness. One first in-cabin smoke exposure eight years previously (no fire on board), with all crew reporting headache, nausea, vertigo, blurred vision.	
Incident:	Residual leak:	Symptoms occurred on three flights where complaints were reported.
Symptoms:	Onset:	Symptoms including tight chest, difficulty in breathing, nausea and abdominal spasms, palpitations, disorientation, feeling intoxicated
	In-flight treatment:	None
	Longer term symptoms:	Alopecia, memory impairment, chronic fatigue, altered coordination, loss of balance, hypothyroidy (not existing prior to exposure), depression.
	Company actions:	Incapacitation acknowledged by social security three years after exposure. Compensation for loss of licence (private insurance).

CASE STUDY No 2

Demographic/occupational	Country:	Canada
Aircraft type:	Fokker 100	Date of incident: May 19, 1989
Occupation:	Cabin crew	Years of experience: more than 10
Age at incident:	35-40	Gender: Female
Medical:	No relevant medical precedent, non-smoker, no alcohol, no recent illness.	
Incident:	Fumes in cabin	One-hour flight. Odours detected and recorded on flight log. Evidence also available of mechanical problems on this flight and ongoing aircraft repairs. Two other cabin crew had similar symptoms, though headaches less severe. Pilot without symptoms, co-pilot reported feeling "intoxicated" and legs very weak, generalised fatigue, inability to stand up and talk.
Symptoms:	Onset:	Initiated during flight, worse during descent. Severe headache, vertigo, loss of balance, nausea, loss of sensation in leg, difficulties in keeping eyes open (probably narcosis).
	In-flight treatment:	Oxygen supply, producing a slight improvement after some time, although difficulties with opening eyes persisted for a few days.
	Post-flight:	A visit to emergency room, four hours after incident - same symptoms as in flight, plus: chest pain, tight chest, heart palpitations, exhaustion, problems in concentration, irritability, feeling intoxicated. Symptoms diagnosed as possible carbon monoxide intoxication, although clinical and biochemical examination normal (concluded that the O ₂ intake during flight corrected the CO exposure)
	Longer term symptoms:	Irritability, somnolence, generalised weakness, "grey out" (incapacity to stand up and talk), weakness, confusion, memory problems, nausea, concentration difficulties, paralysis events (whole body versus left hemiplegia, positively treated by Serax), depression.
	Diagnostic tests:	Neuropsychological tests concluded in reduced visuo-spatial analysis and organisation, reduced visual information retention, altered verbal fluidity for phonologic tests while semantic within normal, reduced analytical reasoning, limited capacity for information evocation, cognitive disorders, depression. No structural anomaly evidenced.
	Symptom persistence:	Symptoms (mainly neuropsychological) have been almost stable over a four year period post-exposure. She has not been able to work for over 4 years after incident.

Company actions:	Occupational exposure acknowledged and compensation for deficit granted 3½ years after the incident.
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CASE STUDY No 3

Demographic/occupational	Country:	Australia
	Aircraft type:	BAe 146
	Occupation:	Cabin crew
	Age at incident:	25-30
	Medical:	Non-smoker, low alcohol. Deteriorating health over previous two years while continuing to work. The following complaints commenced in January 1992: headaches, watery eyes, sinus problems, nausea, swollen glands, dizziness, sleep difficulties, brain fogginess and skin rashes. Oxygen was requested on a flight in June 1992. Blood was coughed up post-flight. Diagnosed for EBV (Epstein Barr Virus) nine months before major incident.
Incident:	Smoke in cabin	1-2 hour flight. Black smoke emitted into the cabin from the air-conditioning ducts, sufficient for passengers to believe a fire had started. Captain vented the cabin but a haze remained sufficient to obscure the back of the plane for the flight. Event logged. Other cabin crew had symptoms of irritation.
Symptoms:	Onset:	Pre-existing symptoms from previous flights exacerbated: Fatigue, headaches, inability to concentrate, skin rash.
	In-flight treatment:	None.
	Post-flight:	Same symptoms as in flight, plus: headaches and head spasms, sinus problems, nausea, eye soreness and pain, exhaustion, problems in concentration, irritability, swollen glands, neuropsychological symptoms, such as giddiness, "brain fogginess", memory lapses, irritability, sleep difficulties, dyslexia.
	Longer term symptoms:	Chronic fatigue, headaches, weakness, confusion, memory problems, nausea, concentration difficulties, depression, multiple chemical sensitivity.
	Diagnostic tests:	Chemically sensitised. Neurological dysfunction in (AERP) auditory evoked response potential test. Metabolic imbalances.
	Symptom persistence:	Some symptoms abated, some declined but flared on chemical exposure, some remained. Symptom-free on holiday in 1997, but symptoms recur on return to city. Now working part time in an unrelated field.
Company actions:		Formed an expert panel that acknowledged irritant effects but repudiated long term effects. Defended a workers compensation case, which was decided against the company in 1999 for exacerbation of pre-existing illness.

CASE STUDY No 4

Demographic/occupational	Country:	USA
	Aircraft type:	B-727
	Occupation:	Cabin crew
	Age at incident:	40-45
	Medical:	No relevant medical precedent, non-smoker, no alcohol, no recent illness.
Incident:	Fumes in cabin:	One-hour flight. Blue haze and "sweet smell" in cabin ten minutes after take-off. Loss of hydraulic pressure detected before take-off and "repaired on tarmac". Aircraft grounded after landing at destination for hydraulic repair. All cabin crew intoxicated, although less severe symptomatology as compared to the present case study. Flight deck crew used oxygen masks and reported no symptoms.
Symptoms:	Onset:	Initiated during flight, ten minutes after take off. Severe headache, dizziness, nausea, sweating, shaking, laboured painful breathing - tight chest and chest pain, incoherence, weakness, stumbling, disorientation, memory impairment, palpitations, tunnel vision, eye burns, loss of consciousness.
	In-flight treatment:	None

Post-flight:	At emergency room on same day and visit the next day: further symptoms to those reported to the in-flight reported symptoms: abdominal pain and cramps, blurred vision and disorientation, altered coordination, blurred speech. Diagnosed as toxic encephalopathy.
Longer term symptoms:	Skin rash and blisters on uncovered body parts, tunnel vision, diarrhoea (for a week), loss of balance, neck/eye pain, alopecia (for 2 months), no menses for 6 months, impairment in cognitive and reasoning problems, altered memory, unstable body temperature, ataxia, muscle weakness, chronic fatigue, seizures.
Company actions:	Compensation for medical bills and partial compensation for loss of income (five years after).

CASE STUDY NO 5

Demographic/occupational	Country:	Australia	
Aircraft type:	BAe 146	Date of incident	30 October 1997 (major exposure event hereunder described, further incapacitated on a flight three weeks later).
Occupation:	Flight crew	Years of experience	15-20
Age at incident:	30-35	Gender:	Female
Medical:	non-smoker, almost no alcohol. No recent illness, against a background of deteriorating health over previous six months. Six years flying BAe 146 with chronic exposure and numerous exposures under pack burnout procedures.		
Incident:	Residual leak:	One to two hour flight. Flying in plane with smell of engine contamination of air. Event logged. Eventually subject to (BASI) Bureau of Air Safety and Investigation report. Eye redness and lacrimation in flight crew. Cabin crew and passengers complaining of smell.	
Symptoms:	Onset:	Nausea, vestibular problems, tunnel vision, "grey out", headaches, sore eyes.	
	In-flight treatment:	None. Was not able to think clearly enough to use oxygen or hand over to first officer.	
	Post-flight:	Visit to general medical clinic immediately after landing. Same symptoms as in flight, plus: scalp numbness, perception displacement, feeling of intoxication, fatigue. Diagnosed as nystagmus / labyrinthitis.	
	Longer term symptoms:	Headaches, and head pressure, weakness, chronic fatigue, concentration and memory difficulties, loss of clarity of thoughts, slurred speech, eye problems including severe nystagmus, accommodation and vision (fluorescent, bright lights, bright background lights) problems, sleep problems, weight loss, nausea and diarrhoea, reactive hypoglycemia, tremors, food and alcohol intolerance, multiple chemical sensitivity, lack of coordination, loss of muscle control in face, head movement sideways or up or down, motion sickness.	
	Diagnostic tests:	CT scan normal. Chemically sensitised. Neurological dysfunction in auditory evoked response potential AERP test. Metabolic imbalances.	
	Symptom persistence:	Some symptoms abated, some declined but flared on chemical exposure, some remained. Unable to pass aviation medical test for flying licence. Not working since incident.	
Company actions:	Suspended flying licence. formed expert panel that acknowledged irritant effects but repudiated long term effects		

CASE STUDY NO 6

Demographic/occupational	Country:	Australia	
Aircraft type:	BAe 146	Date of incident:	November 1997
Occupation:	Cabin crew	Years of experience:	10-15
Age at incident:	30-35	Gender:	Female

	Medical:	non-smoker, low alcohol. No relevant medical precedent, but deteriorating health over previous twelve months, including headaches, nasal congestion, sinus problems, hyposmia.
Incident:	Residual leak:	Three days of short and long haul flights up to eight hours/day with reported air quality problems and complaints. The situation of oil leaks/inoperative filters detailed in Engineers and Flight reports. All three cabin crew taken to hospital post-flight.
Symptoms:	Onset:	Overcome by fumes. Exacerbation of fatigue, inability to concentrate, coordination and speech impairment, body paralysis lasting few minutes, swelling, nausea, pain in left temple, breathing difficulties, dilated pupils, bloodshot eyes.
	In-flight treatment:	None.
	Post-flight:	Same symptoms as in flight, plus: intense headaches, nausea, eye soreness and pain, exhaustion, problems in concentration, irritability, neuropsychological symptoms, skin rash, skin colour grey, impaired vision, bruising of legs.
	Longer term symptoms:	disorientation, reactive hypoglycemia, confusion, poor concentration, impaired memory, short term memory loss, grey in colour for 7 months, dilated pupils, constricted breathing (sometimes), chronic fatigue, nausea, gastrointestinal problems, food and alcohol intolerance, irritability, alopecia, dermatitis, conjunctivitis, pressure and sharp head pains, chemically sensitive, motion sickness.
	Diagnostic tests:	Neurological dysfunction in AERP, metabolic imbalances.
	Symptom persistence:	Many symptoms remain, two years after incident.
	Company actions:	Established odour committee and collected samples. Formed expert panel that acknowledged irritant effects but repudiated long term effects. One cabin crew was granted workers compensation for 1 day. This crew member denied workers compensation but was granted leave to proceed for negligence/damages against airline/employer.

CASE STUDY NO 7

Demographic/occupational	Country:	Australia
	Aircraft type:	BAe 146
	Occupation:	Flight crew
	Age at incident:	30-35
	Medical:	non-smoker, low alcohol. No relevant medical precedent, but deteriorating health 1994-97, including headaches, nasal and throat problems, stridor, nausea, fatigue/lethargy, loss of concentration.
Incident:	Residual leak:	Planes generally contained odours regularly throughout final three years of flying (worse on ground, takeoff, climb, descent). Exposures on occasion were intense enough to cause temporary incapacitation.
Symptoms:	On exposure:	Upper airway irritation, hoarseness leading to loss of voice (eventually requiring surgery), headaches and head pressure, fatigue becoming worse over time, inability to concentrate, (all these symptoms would begin soon after switching on the air conditioning and abate quickly when leaving the plane). Later symptoms include nausea and development of sensitivity to chemicals in and around the airport environment.
	In-flight treatment:	None. Hand over to other flight officer on occasion.
	Last two days:	All symptoms as above, abating on the first day, and increasing on the second day. Symptoms continued, followed by massive increase in head pressure (sufficient to presuppose a stroke had occurred), fatigue, weakness, loss of voice within 24-48 hours.
	Longer term symptoms:	Headache and head pressure, numbness, tingling, dizziness, reactive hypoglycemia, confusion, poor concentration and information processing, impaired memory, short term memory loss, feeling as though not enough oxygen is getting to the body, chronic fatigue, nausea and vomiting, food and alcohol intolerance, skin rashes, chemically sensitive.
	Diagnostic tests:	Neurological dysfunction in AERP, evidence of injury to CNS in neuropsychological tests, abnormality in lung diffusion test.

Symptom persistence: Many symptoms remain, over three years after last exposure. Unable to pass aviation medical test for flying licence. Not working since last exposure.

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Aerotoxic syndrome: a descriptive epidemiological survey of aircrew exposed to in-cabin airborne contaminants

C WINDER

P FONTEYN

J-C BALOUET

Chris Winder, BA (Hons), MSc, PhD, is Associate Professor and Head of the School of Safety Science, and Petra Fonteyn, BSocSc (Hons), is a Research Associate in the School of Safety Science, both at The University of New South Wales. Jean-Christophe Balouet is the Managing Director of Environmental International, an environmental research and consulting organisation in France.

Address for correspondence: Associate Professor C Winder, School of Safety Science, The University of New South Wales, Sydney, NSW 2052, Australia.

The term "aerotoxic syndrome" was proposed in 1999 to describe the association of symptoms observed among flight crew and cabin crew who have been exposed to hydraulic fluid or engine oil vapours or mists. A descriptive epidemiological study was conducted to investigate the health effects of aircrew through a questionnaire mail-out. Most of the respondents (88%) reported that symptoms occurred after exposure to engine oil or hydraulic fluid leaks which caused odours and/or visible contamination in the cabin. Invariably, aircrew directly attributed their symptoms to exposure to in-cabin airborne contaminants. A comparison between 18 respondents from the United States and the 50 Australian respondents shows significant similarities in reported symptoms. There was sufficient commonality in reported symptoms to conclude a symptom basis for aerotoxic syndrome.

KEYWORDS

- AVIATION INDUSTRY
- AEROTOXIC SYNDROME
- NEUROTOXICITY
- NEUROPSYCHOLOGICAL DYSFUNCTION
- AIRBORNE CONTAMINANTS

Introduction

The oils and hydraulic fluids used in aircraft engines can be toxic, and specific ingredients of oils can be irritating, sensitising and neurotoxic (including phenyl-alpha-naphthylamine, and tri-aryl phosphates such as tri-ortho-cresyl phosphate).^{1,2} If oil or hydraulic fluid leaks occur, this contamination may be in the form of unchanged material, degraded material from long use, or combusted or pyrolysed materials. These materials can contaminate aircraft cabin air in the form of gases, vapours, mists and aerosols. There are a number of possible situations that can arise whereby cabin air can become contaminated.³ Significant contaminants include: aldehydes; aromatic hydrocarbons; aliphatic hydrocarbons; chlorinated, fluorinated, methylated, phosphate and nitrogen compounds; esters; and oxides.^{4,6} An additional problem is the lower partial pressure of oxygen in the cabins of aircraft flying at altitude.⁷

To date, most studies that have been carried out to measure atmospheric contamination in aircraft as a result of engine oil or hydraulic fluid leaks are sufficiently flawed on procedural and methodological grounds so as to render their conclusions invalid. Further, no monitoring has occurred during a leak.

International aviation legislation such as the United States Federal Aviation Regulations and the airworthiness standards for aircraft air quality state that "crew and passenger compartment air must be free from harmful and hazardous concentrations of gases or vapors".⁸ Where contamination of the air in flight decks and passenger cabins occurs that is sufficient to cause symptoms of discomfort, fatigue, irritation or toxicity, this contravenes such standards and legislation.

Inhalation is an important route of exposure, with exposure to uncovered skin being a less significant route (for example, following exposure to oil mists or vapours). Ingestion is unlikely.

Occasionally, such exposures may be of a magnitude to induce symptoms of toxicity. In terms of toxicity, a

growing number of aircrew are developing symptoms following both short-term and long-term repeated exposures, including dizziness, fatigue, nausea, disorientation, confusion, blurred vision, lethargy and tremors.^{9,11} Neurotoxicity is a major flight safety concern, especially where exposures are intense.¹²

The earliest case found in the literature was reported in 1977.¹³ A previously healthy member of an aircraft flight crew was acutely incapacitated during flight with neurological impairment and gastrointestinal distress. His clinical status returned to normal within a day. The aetiology of his symptoms was related to an inhalation exposure to aerosolised or vapourised synthetic lubricating oil arising from a jet engine of his aircraft.

Other studies of chemical exposures in aircraft can be found in the literature, including a 1983 study of 89 cases of smoke/fumes in the cockpits of US Air Force aircraft, a 1983 study of Boeing 747 flight attendants in the US (this article linked the symptoms to ozone), a 1990 study of aerospace workers, and a 1998 study of BAe 146 flight crews in Canada over a four-month period.^{9,14-16} A recent report of seven case studies considered to be representative of the common symptoms of irritancy and toxicity described similar symptoms.¹⁰ They investigated different exposures and situations, and the range of symptoms in these studies was quite broad, affecting many body systems. However, there are common themes in symptom clusters in these studies, as shown in Table 1.

While Table 1 shows a long list of symptoms, it is possible to characterise many symptoms more consistently. For example, different studies may describe the same symptom as dizziness, loss of balance, light-headedness, feeling faint, feeling intoxicated, or disorientation. It would be incorrect to regard such symptoms as being entirely different from each other — they point to a basic neuropsychological dysfunction affecting balance. But, rather than dismissing such symptoms as being multitudinous and variable, it may be more appropriate to re-categorise symptoms with clearer definitions, so that the artificial distinctions between symptom reporting can be clarified, and a shorter list developed.¹⁷

TABLE 1
Studies reporting signs and symptoms in aircrew

Symptoms	Number of cases/reports				
	89 ¹⁴	248 ¹⁵	53 ¹⁶	112 ⁹	7 ¹⁰
Irritation of eyes, nose and throat					7/7
Eye irritation, eye pain	35%	74%	57%	24%	4/7
Blurred vision, loss of visual acuity	11%	13%		1%	4/7
Rashes, blisters (uncovered body parts)			36%		4/7
Sinus congestion	35%	54%		5%	2/7
Nose bleed		17%			1/7
Throat irritation, burning throat, gagging and coughing	2%	64%	57%	43%	2/7
Cough		69%			2/7
Difficulty in breathing, chest tightness		68%			3/7
Loss of voice		35%			1/7
Chest pains	7%	81%		6%	2/7
Respiratory distress, shortness of breath, breathing problems requiring oxygen		73%		2%	4/7
Fainting, loss of consciousness, "grey out"	4%	4%			3/7
Shaking, tremors, tingling	9%			3%	3/7
Numbness (fingers, lips, limbs), loss of sensation			8%	2%	4/7
Dizziness, loss of balance	47%			6%	4/7
Light-headedness, feeling faint or intoxicated	35%	54%		32%	7/7
Disorientation	26%			15%	4/7
Severe headache, head pressure	25%	52%		26%	7/7
Trouble thinking or counting, word blindness, confusion, coordination problems	26%	39%	42%		6/7
Memory loss, memory impairment, forgetfulness			42%		7/7
Behaviour modified, depression, irritability	26%	20%	60%		4/7
Nausea, vomiting, gastrointestinal symptoms	26%	23%	15%	8%	6/7
Abdominal spasms, cramps, diarrhoea	26%				3/7
Change in urine		3%	6%		
Joint pain, muscle weakness, muscle cramps		29%			2/7
Fatigue, exhaustion					7/7
Chemical sensitivity			32%		4/7

Against this background, a descriptive epidemiological study was conducted of aircrew, which investigated the development of symptoms during flight through the mail-out of a self-administered questionnaire. Because of industry sensitivities with regard to such a survey, it was designed to be independent of the aviation industry (that is, aircraft manufacturers, airline operators and unions were not involved in the design

or conduct). Therefore, there was no formal process of requesting nominations and a description of survey objectives was not provided prior to nomination.

One of the aims of the present study was to identify whether aerotoxic syndrome was definable and, if so, the symptoms that might be considered indicative of such a condition.

Methodology

The survey

Selection process: The survey was voluntary. Survey participants were those aircrew who took the effort to identify themselves to the research project team as being interested in the survey, and who then agreed to complete and return the survey.

As noted above, there was no information or publicity prepared or circulated by the research team about the proposed survey. Officers in both flight attendants and pilots unions were aware of the study, and a statement was issued by the Flight Attendants' Association of Australia that it was not involved with the survey. Further, information flows rapidly within the Australian aviation industry and the principal investigator received many telephone and email inquiries. Some inquirers were suspicious about the independence of the survey, about the source of research funding and about the possibility that the survey had any undue influence from companies or unions. Many nominations were made only when guarantees of funding independence and assurances of nominator anonymity were provided by the research project team.

The aircrew volunteer database was compiled over a four-month period in late 2000. It was originally proposed to survey between 30 and 50 nominations, but it became apparent that this was an underestimate of those interested in participating. Eventually 117 aircrew volunteered to be part of the survey. Of these, 100 were nominations from Australian aircrew.

Survey mail-out: Survey questionnaires were sent out in January 2001. A response period of four months was specified. After this time, no further responses were included. Other responses have been received since the cut-off date, including 18 from two US airlines. Because the highest response rate was from Australian aircrew, data from Australian respondents are presented in this article, with a comparison between the Australian and US findings discussed later.

Response rate: Ultimately, 100 survey forms were sent out to Australian nominations and 50 replies were received (a response rate of 50%). As distinct from many other surveys, the research team did not send follow-up reminders to non-respondents. It is not known why 50 volunteers initially planned to be involved in the survey but then later declined. A response rate of 50% to a single mail-out is considered excellent, and could have been higher if there had been a follow-up to non-respondents.

Development of questionnaire

A three-page structured questionnaire was developed to survey aircrew volunteers. The questionnaire consisted of open-ended and closed questions, with extra space to add other comments.

The questionnaire was derived from pre-existing questionnaires that had been developed for collecting information at interviews to assess the experience of aircrew following adverse health outcomes from exposure to contaminants while flying.¹⁰ Additions and modifications were made to the questionnaire to suit the present study. The questionnaire used in the present study was reviewed by the University of New South Wales Ethics Committee. It was considered that the questionnaire should not "lead" or prejudice the respondent, and extensive modifications were made to early drafts to ensure neutral language. The final questionnaire did not contain concepts such as air leaks, contamination or aerotoxic syndrome. The questionnaire was then trialled with 10 aircrew. Further, mainly editorial, modifications were made as a result of the trial.

Aircrew were initially asked to identify what, if any, health symptoms they had experienced while flying and the duration of these symptoms. These questions were open-ended and invited opportunities for in-depth qualitative responses. Respondents were asked to describe factors that may have contributed to any adverse health symptoms and outcomes.

The second part of the questionnaire consisted of a relatively long list of signs and symptoms within the following symptom categories: neuropsychological;

neurological; senses; eye and skin; respiratory; cardiovascular; gastrointestinal; renal; endocrine; immunological; and reproductive. Respondents were asked to report whether they had experienced any of the listed symptoms.

Data analysis

Qualitative data were analysed by using the Statistical Package for the Social Sciences.¹⁸ Given the possibility of selection and reporting bias, statistical analysis was not conducted on these data.

Qualitative open-ended responses were documented and descriptive quotations are included in this article.

Results

Demographic characteristics

Table 2 contains a demographic overview of respondents. Of the 50 crew surveyed, 28% were male and 72% were female. The majority of respondents were cabin crew (70%), with flight crew comprising the remaining 30%.

The age of respondents ranged from 26 years to 59 years, with a mean age of 40 ± 8 years (the median was 38 years).

Years of experience in the industry ranged between two and 40 years. The mean number of years of experience in the aviation industry was 16 ± 10 years.

Ansett employed 72% of respondents and National Jet Systems 22%. Most flew on BAe 146 aircraft (92%), with 56% flying the A320 aircraft. Several cabin crew flew both types of aircraft.

The vast majority of respondents (92%) reported that they were non-smokers and tended to abstain from alcohol (16%) or consume small quantities of alcohol occasionally (72%).

Contributing factors

Aircrew were asked to describe any factors that may have contributed to their symptoms. These questions were unprompted and individual open-ended

comments were requested. Most of the respondents (88%) reported that their symptoms occurred after an assumed exposure to oil gases and fumes in the cabin. The common use of the word "fume" was often incorrect on technical grounds. Technically, a fume is an aerosol of solid particles generated by condensation from the gaseous, volatile or oxidised atomic state — not what were almost certainly vapours (the gaseous phase of a liquid at room temperature) or mists.

Invariably, respondents attributed these gases and "fumes" (vapours and mists) to possible oil leaks. As the nature of these exposure events cannot be adequately described in statistics and graphs, a few extracts from some of the respondents are reproduced below. These sometimes better describe the more alarming aspects of such exposures:

- Pilot, age 59: "I consider the symptoms suffered are a direct result of cockpit fumes on the BAe 146 aircraft. The greater the incidence of detectable fumes, the more apparent the symptoms ... also related to rate of flying. On leave, the symptoms reduced."
- Flight attendant, age 48: "I had an increased exposure of fumes on the BAe 146, when the cabin filled up with smoke, I could not see past row two on the aircraft. Since that incident both the Captain and First Officer have developed lung disease, I had breast cancer and another flight attendant has sued the airline because of health problems."
- Flight attendant, age 37: "Following the fume occurrence on the BAe 146 I had a metallic taste in my mouth, headache over the right eye, sore throat. Short-term symptoms included nausea, dizziness, lack of concentration, memory loss, stiff neck, stinging/itchy, weepy eyes, difficulty in concentrating while driving, 'heavy' head, unable to stand in the shower without falling over."

Over half of the respondents (54%) cited airconditioning problems as a reason for adverse health symptoms. Other factors included hypoxia (18%) and pressurisation problems (16%).

TABLE 2
Overview of the aviation employees surveyed

Aviation employee characteristics	Categories	Number of responses	
		n	%
Gender	Male	14	28
	Female	36	72
Age	20–29	4	8
	30–39	25	50
	40–49	13	26
	50–59	8	16
Years of experience in aviation industry	1–9	13	26
	10–19	19	38
	20–29	11	22
	30–39	5	10
	40+	2	4
Occupation	Flight crew	16	32
	Cabin crew	34	68
Airline	Ansett	36	72
	National Jet Systems/Airlink	12	24
	Northwest Airlines	2	4
Type of aircraft*	BAe 146	46	92
	A320	28	56
Alcohol	None	8	16
	Mild	36	72
	Moderate	5	10
	Heavy	1	2
Smoking	Current smoker	4	8
	Non-smoker	46	92

* This was a multiple response question, so the percentage was calculated by each item as a total of 50 responses.

Onset of symptoms

Adverse health symptoms as a result of exposure to oil fumes were reported by 47 (94%) of the respondents.

Almost all respondents (96%) reported adverse symptoms immediately while flying or on the same day as flying. A large number of respondents (82%) also experienced adverse symptoms that continued for at least one month from the time of exposure. Many respondents (74%) reported that they experienced symptoms for at least six months after exposure. The term “long-term effects” indicates an effect(s) persisting over a long period of time; however, the duration of what might be considered “a long period of time” has generated debate in this industry. Some view this as being at least over six months, others over decades. For the purposes of this article, an effect is

considered long-term if it has been present for over a year. Long-term symptoms that remained or developed after at least one year of exposure were reported by 76% of respondents.

Amelioration of effects of exposure

Data on the manner in which effects of exposure were ameliorated are shown in Table 3. Under half of the respondents (42%) had mild symptoms that reduced on vacating the plane and subsided further after extended rest.

Those with more moderate symptoms (32%) used the oxygen on board the aircraft:

— **Flight attendant, age 37:** “At times, due to maintenance problems, aircraft are flown with one

TABLE 3
Amelioration of effects of exposure (including gender differences)

Gender	What happened					
	Fresh air/ sleep on landing	Oxygen used	Hospitalised	Doctor attended	N/A or no symptoms	Total %
Male*	10 (20%)	2 (4%)	0	0	2 (4%)	14 (28%)
Female*	11 (22%)	14 (27%)	8 (16%)	3 (6%)	0	36 (72%)
Total*	21 (42%)	16 (32%)	8 (16%)	3 (6%)	2 (4%)	50 (100%)

* Data expressed as number of respondents (%) (total n = 50).

airconditioning pack in service. I usually feel hypoxic on these flights and use oxygen. On other occasions, the problem is with oil leaks and then my symptoms re-occur. As I have removed myself from flying on the BAe 146 my symptoms have subsided.”

- **Flight attendant, age 40:** “After the mechanical failure, hydraulic fuel leaked into the cabin. All of the cabin crew and four passengers became ill. Flight deck was on oxygen when the crew reported dizziness, nausea and confusion and extreme head pain.”

One pilot was so affected by exposure that the aircraft was grounded until the symptoms subsided. Almost one quarter of respondents (22%) experienced severe symptoms and collapsed after exposure. Hospitalisation was necessary for 16% who were taken off the aircraft on a stretcher or wheelchair suffering from exposure to toxic fumes:

- **Flight attendant, age 40:** “All the cabin crew and some passengers were exposed to the fumes. My legs gave way ... I had to harness myself into my jump-seat. After landing, the crew were taken by company van to an emergency room. Hospitalised, the physician’s diagnosis five hours after landing was probable inhalation injury — cognitive problems, speech slurred, headache, nausea. Twenty-four hours after exposure the Internist Doctor noted ataxia, coordination problems — diagnosis toxic encephalopathy. Day 3, the Neurologist documented toxic encephalopathy with significant cognitive

dysfunction, memory loss, speech disorder — I cannot set a clock and cannot draw a cube. An MRI was given two days after incident, tissue damage was found in white matter, high signal intensity spots on the frontal lobe of the brain. Still experience long-term effects.”

- **Flight attendant, age 24:** “On the day of the incident, within the first hour of smelling the fumes I had difficulty breathing and talking. I had spasms in my legs, was faint and felt very hot. On disembarking I fell to the floor, they put me on oxygen and wheeled me off in a wheelchair. I was on oxygen for the first hour in the first aid room and was unable to talk for the first hour. I was taken to the medical centre during which time I was in and out of consciousness.”

On a gender basis, fresh air and sleep reduced symptoms for almost equal numbers of males (20%) and females (22%); however, females generally experienced more severe symptoms that required greater medical intervention. Females (28%) were over five times more likely to use oxygen than males (4%). Hospitalisation was required for 16% of females in comparison with no males requiring hospitalisation. Three women (6%) required attendance by a doctor, as opposed to no reported requirements for males seeking medical assistance (see Table 3).

Data on signs and symptoms

Data on symptoms are presented below on the basis of grouped symptoms or organ systems. Data are presented in graphical form, with the same axis

dimension for respondents showing symptoms to make comparison easier. Where possible, data on the background incidence of such symptoms in the Australian population are provided to allow a comparison with background incidence, although comparison of the data below with the other forms of data may be problematic (for example, self-reported as opposed to physician-collected data). There are also problems with comparing total populations with workers in that the "healthy worker" effect may bias results, as would comparing males with females.^{19,20}

Irritancy symptoms in eyes, skin and respiratory system

There are high levels of irritancy symptoms in the data presented in Figure 1, including eye irritation (76%) and skin problems (58%). These are consistent with exposure to an irritant, but this may not be the only cause (for example, they could also be caused by the low humidity in aircraft during flight). There are some gender differences, although these could be related to gender sample sizes.

Similarly, a number of the symptoms in Figure 2 show respiratory irritation, with 64% of respondents reporting breathing problems (75% in females) and 48% reporting chest tightness/wheezing.

There are problems in categorising self-reported symptoms such as breathing problems or respiratory irritation. There are some gender differences in the data, with apparently high rates of respiratory irritation in females.

Adverse respiratory health effects from exposures to, among others, oxides of nitrogen, ozone, sulphur dioxide and particulates either singularly or in combination, such as in exposure to aviation fuel or jet stream exhaust, have been known for some time.^{1,9,11,14} Tunnicliffe et al found an association between high occupational exposures to aviation fuel or jet stream exhaust and excess upper and lower respiratory tract symptoms — in keeping with exposure to a respiratory irritant.²¹ In their study, 51% of aviation workers had upper and lower respiratory symptoms, including cough with phlegm and runny nose.

Gastrointestinal/renal signs and symptoms

Nausea and vomiting are relatively common symptoms, and were reported by 58% of respondents.²² In most cases these symptoms were associated with intensifying gastrointestinal symptoms (mainly in females) of abdominal spasms (20%), abdominal pain (10%) and diarrhoea (28%) (Figure 3).

Neuropsychological and neurological signs and symptoms

Symptom reporting rates were high for many neuropsychological symptoms, including intense headache (86%), dizziness and disorientation (72%), performance decrement (including changes in cognitive function) (70%), memory and recall problems (66%), and balance problems (62%) (Figure 4). Other symptoms, such as anxiety (50%) and depression (40%) are more global and harder to interpret. The consistency of neurological symptoms is quite striking, suggesting neuropsychological impairment of a general nature, as seen, for example, in exposure to volatile organic compounds, organophosphate compounds or carbon monoxide.²³⁻²⁵ The significance of such phenomena remains problematic.²⁶

While neuropsychological effects are often dismissed as being subjective or unquantifiable, intense headache at 86%, dizziness/disorientation at 72%, performance decrement at 70% or memory problems at 66% are not symptoms that should be dismissed in aircrew while performing their duties. The high rate of respondents reporting such effects is difficult to interpret, owing to the self-selection of respondents to, and reporting bias in, this survey. However, the incidence of neuropsychological symptoms in aircrew, especially in females, appears excessive.

While self-reporting of neuropsychological or neurological symptoms may contain elements of subjectivity, the incidence in both genders of neuropsychological or neurological symptoms such as tingling (40%), tremors (30%), seizures or loss of consciousness (14%) was based on the reporting of symptoms after a respondent had been examined by

FIGURE 1
Data on eye and skin irritation signs and symptoms

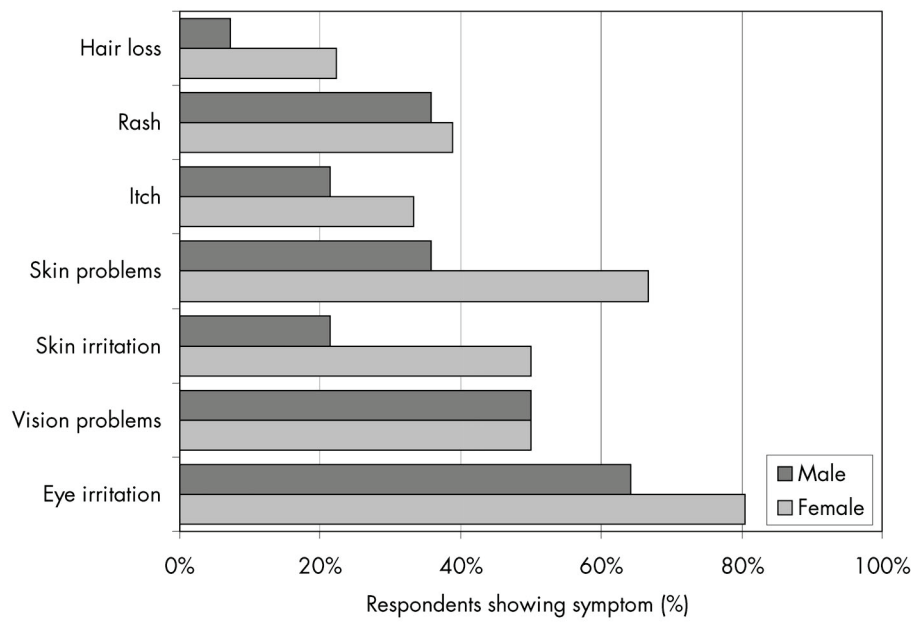


FIGURE 2
Data on respiratory and cardiovascular signs and symptoms

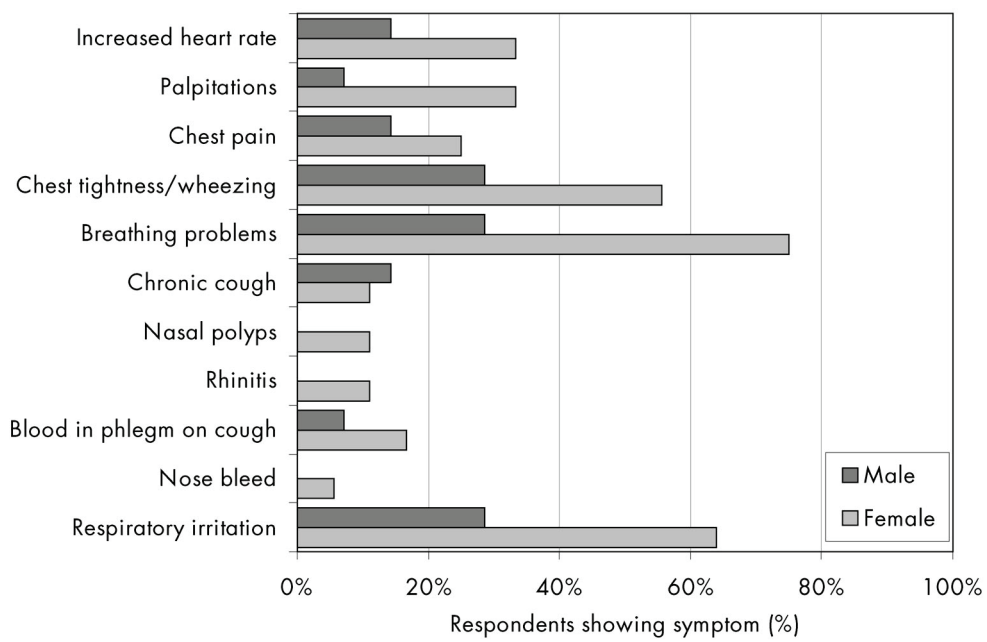
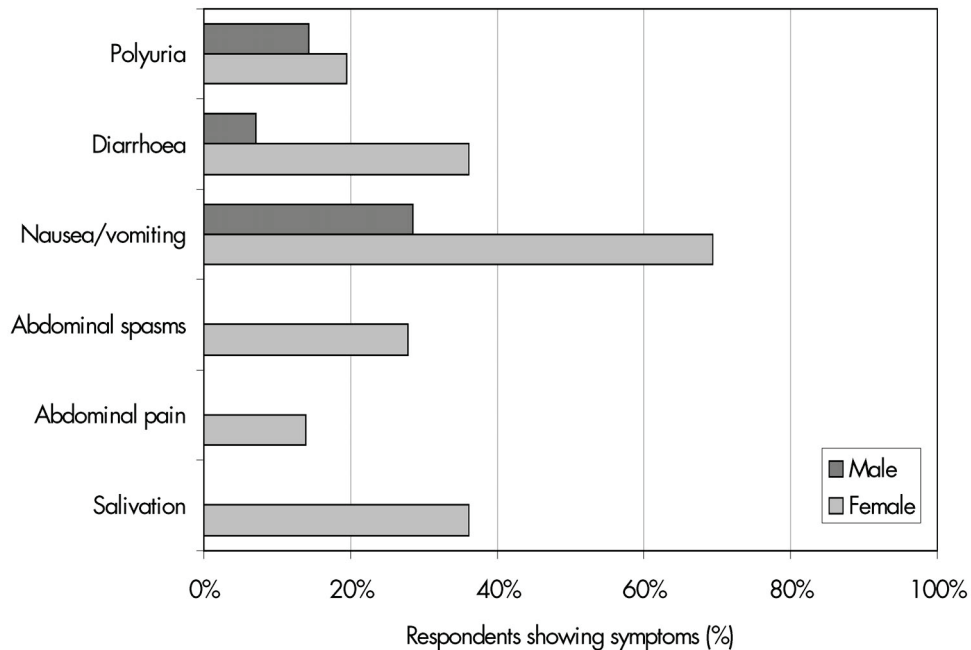


FIGURE 3
Data on gastrointestinal/renal signs and symptoms



their medical practitioner (Figure 5). These are significant symptoms that point to a toxic aspect of the exposures reported by respondents. Further, there may be a neurotoxic component to other symptoms, such as vision problems or disorientation or balance problems.

Reproductive signs and symptoms

There were 36 female respondents. All were of reproductive age, and many were planning to have or were having families during the time of their employment. Working women tend to have a lower fertility rate than non-working women, although this is for employment rather than biological reasons.²⁷ Fertility rates are falling in the developed nations for a range of reasons, and are estimated at 7–10%.²⁸ The data from respondents for reproductive symptoms are shown in Figure 6. Infertility was reported by 33% of respondents. This appears to be above population norms.

Menstrual dysfunction (variously reported as heavy periods, irregular periods or dysmenorrhoea) was reported by 28% of female respondents, miscarriage by 14% and multiple miscarriage by two respondents. Of particular significance is the problem of neonatal death in two respondents and genetic problems in the offspring of three respondents. While the sample size is small, these are noteworthy findings.

General signs and symptoms

As well as signs and symptoms in specific organ systems, a range of multi-organ or general symptoms was reported (Figure 7).

Joint pain (arthralgias) and muscle pain (myalgias) are common symptoms resulting from a variety of disease processes.^{29,30} Despite the poorly understood pathogenetic mechanisms underlying myalgia and arthralgia, they are common in chronic fatigue and chemical sensitivity syndromes.

FIGURE 4
Data on neuropsychological signs and symptoms

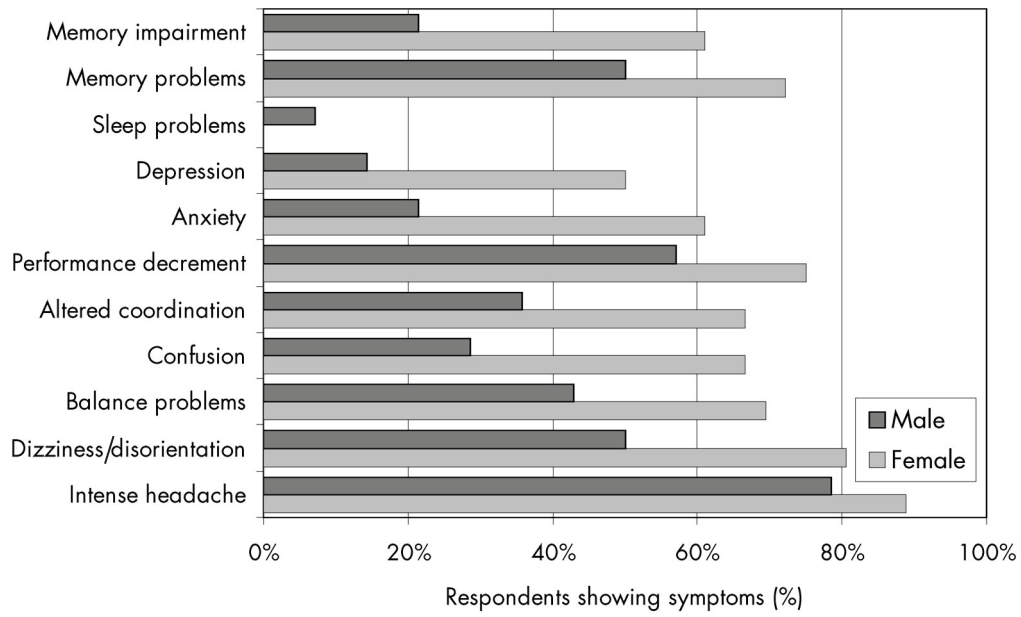


FIGURE 5
Data on neurological signs and symptoms

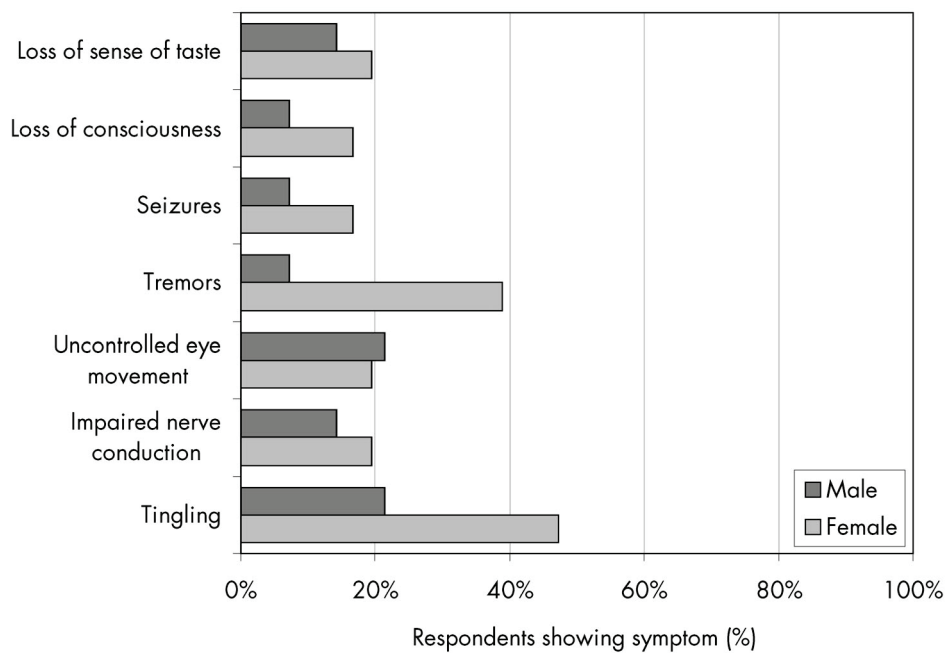
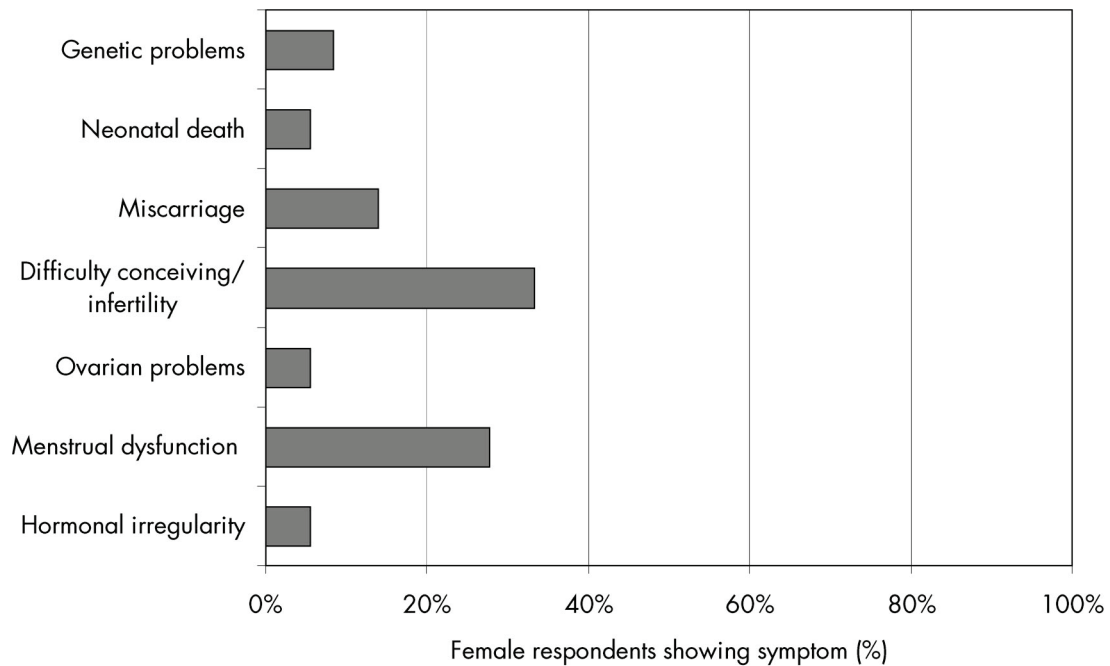


FIGURE 6
Data on reproductive signs and symptoms

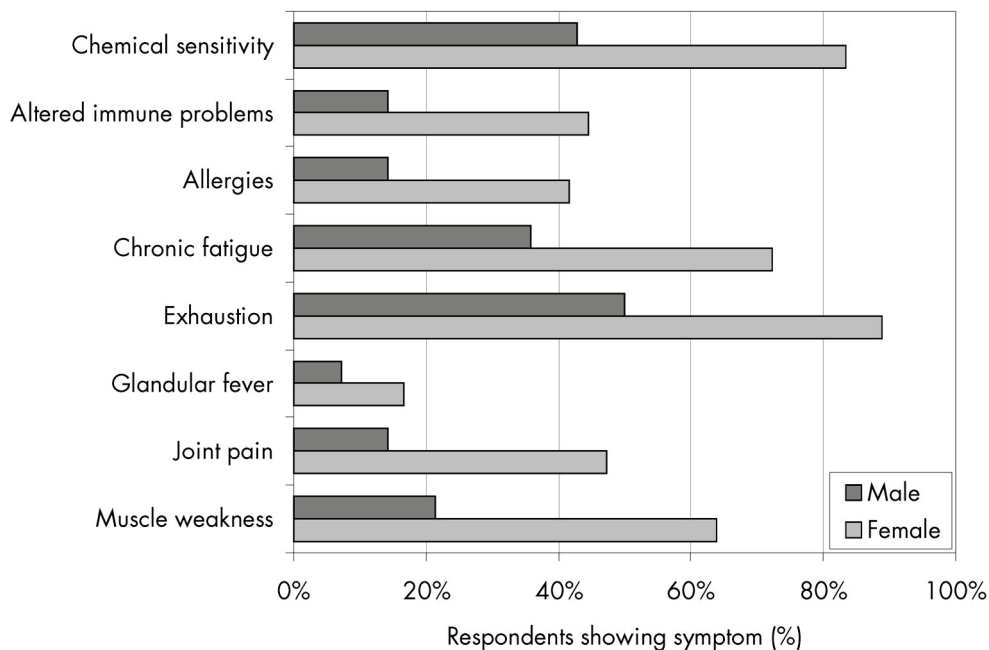


Of the symptoms reported in this survey, exhaustion was the second most common, being reported by 78% of all respondents (89% of female respondents). Fatigue is an established hazard in aviation — from the perspective of the impairments in alertness and performance that it creates in pilots.³¹ The exhaustion reported by respondents escalated into 72% of respondents reporting chronic fatigue. Prolonged or chronic fatigue is reported by about 25% of all patients presenting to Australian general practice.³² Such fatigue states represent a continuum of severity ranging from the mild and transient symptoms through to the more rare, severe and prolonged fatigue disorders. In about 1% of patients attending general practice in Australia, the fatigue state will meet diagnostic criteria for chronic fatigue syndrome.³² Figure 7 shows chronic fatigue at 36% for males and 72% for females. While there may be differences between diagnostic criteria for, and self-reporting of, chronic fatigue, these rates (particularly in females) are still very high.

A second cluster of symptoms was observed with chemical sensitivity. Allergies were reported by 34% of respondents, altered immune problems by 36% of respondents, and chemical sensitivity by 72% of respondents (83% of female respondents). Again, these are high rates that would almost certainly be well above any population background rate.

The co-occurrence and overlapping of many of the symptoms reported by the respondents is in keeping with comparable investigations. Co-morbidity of chronic fatigue, irritable bowel syndrome, chemical sensitivity, chronic headache and other unexplained conditions has only recently been systematically studied.³³ Comparative investigations in referral clinic populations have reported that in 53–67% of persons with chronic fatigue syndrome, illness worsens with exposure to various chemicals. Many patients with chronic fatigue syndrome also have irritable bowel syndrome (63%), multiple chemical sensitivity (41%) and other unexplained illness.³³

FIGURE 7
Data on general signs and symptoms



The US questionnaires

Eighteen questionnaires were submitted from respondents with addresses in North America (16 female; two male). Again, these were analysed descriptively. Rather than presenting the same data again (as in Figures 1 to 7), the symptom incidence for each symptom was plotted using an X,Y scatterplot, with the horizontal axis (X-axis) being the Australian symptom percentages and the vertical axis (Y-axis) being the US percentages (Figure 8).

These data show a number of symptoms where there is some difference between Australian and US symptom incidences, although in a few cases these outliers suggest diagnostic differences between the two countries (for example, chemical sensitivity/allergy). Nevertheless, there is a remarkable correlation between these data (correlation coefficient $r = 0.859$, $r^2 = 74\%$).

Discussion

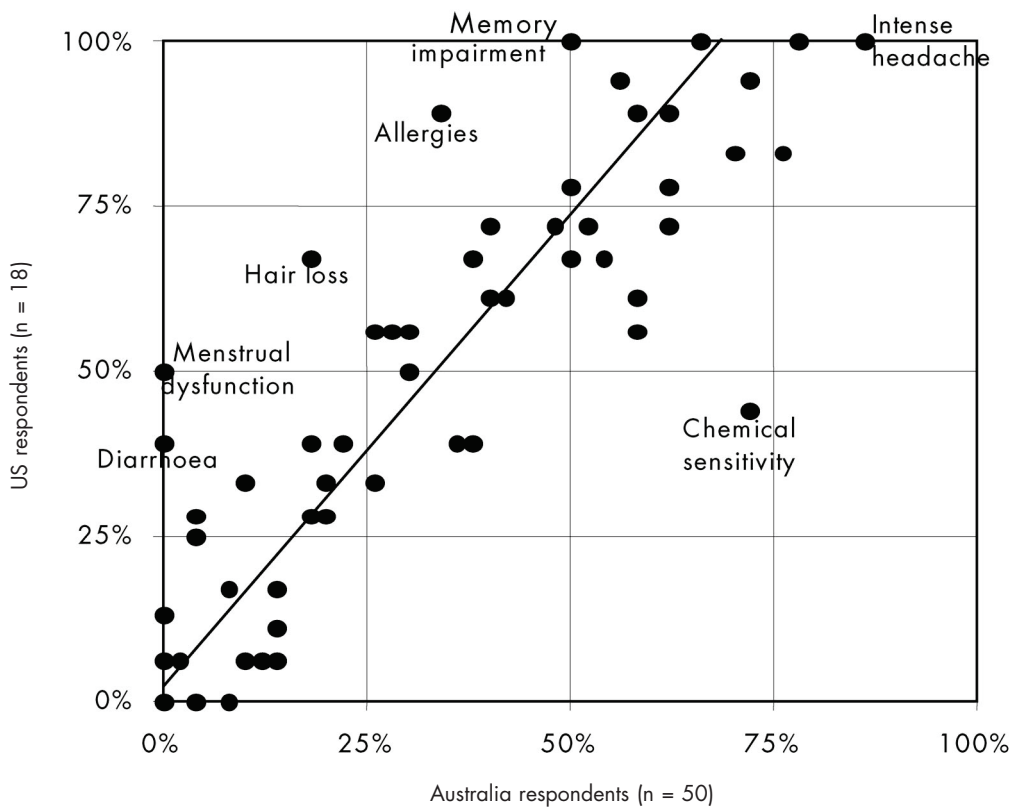
The term "aerotoxic syndrome" was proposed in 1999 to describe the association of symptoms observed among aircrew who have been exposed to hydraulic fluid or engine oil smoke/fumes.^{10,34}

With regard to the use of the term "syndrome", this is used to describe a set of symptoms that occur together, although generally there is no specification for the type and number of symptoms. Further, experience would suggest that the range and types of symptoms in such a symptom cluster would not be large.¹⁷

With regard to exposure to contaminants, while such exposures were not common, they were relatively frequent in certain models of aircraft. This study found two main types of exposure:

1. an "exposure event", where there was at least one self-reported intense exposure to contaminated air from an engine oil or hydraulic fluid leak; and

FIGURE 8
Comparison of Australian and US symptom incidences



- self-reported residual exposure to odours and non-visible contamination.

While the majority of exposure events occurred during flight, it should be stressed that a number of leaks and exposures occurred on the ground. Engine seals are less efficient during engine warm up, during ground manoeuvring, and during transient operations (acceleration/deceleration). Further, prior to 1998, an operational procedure on some models of aircraft called an auxiliary pack unit burn out was carried out every day, whereby heated engine air was pumped through the passenger cabin to decontaminate heat exchangers, air ducts and filters. While operational procedures expressly excluded any person from being on the aircraft during pack burns, from 1992 to 1997 it was common for flight

attendants to carry out early morning pre-flight checks on aircraft during pack burns — therefore, aircrew were exposed to contaminants. So, although major exposure events occurred during flight, ground operations should not be excluded as a source of exposure.

Although it was not possible to quantitatively assess exposure during exposure events, descriptions from visible haze to dense smoke suggest significant exposure.

Immediately after exposure, the symptoms are essentially those that can be observed in individuals who have been exposed to toxic irritants, such as eye irritation, respiratory irritation, headache and other short-term neuropsychological effects, skin problems and nausea. These symptoms usually recede after

cessation of exposure. At least two Australian airlines have admitted that exposure events are significant enough to produce symptoms of irritation.^{35,36}

However, it became apparent during this study that not all symptoms receded following cessation of exposure. Some existing symptoms became more debilitating, for example, headaches became so intense that they lasted for weeks and would not respond even to the most powerful over-the-counter analgesics. Neuropsychological symptoms became more generalised and affected more functions, with cognitive symptoms and recall problems becoming more significant. Skin itch became skin rash. Respiratory irritation became chest pain and/or difficulty in breathing. The intensification process was more likely to occur if exposure continued but, occasionally, would intensify even if exposure had ceased.

In addition, new symptoms began to emerge, including chronic fatigue, parathesias and numbness, myalgias, arthralgias, alcohol and food intolerances, and chemical sensitivity. Most of these symptoms continued even after exposure had ceased. Further, these and many of the neurological and neuropsychological symptoms worsened.^{9,11}

The number of cases that emerged over the 1996 to 1999 period in Australia, North America and Europe became significant — to the extent that an appropriately designed epidemiological survey of aircrew was needed. The possibility of an industry-sponsored study seemed unlikely. Therefore, the present independent survey was conducted.

This survey comprised 117 individuals who nominated themselves to be entered into a database to receive a copy of the survey questionnaire. There were no criteria used to select study participants. The survey was carried out after a well-publicised Australian Senate Inquiry into air quality in the aviation industry, and this may have increased interest in some individuals to self-nominate.³⁷ The fact that so many respondents who had flown on those aircraft where engine leaks had occurred returned questionnaires was not intrinsically part of the survey. It is almost certain that self-nominations occurred

through word of mouth as a result of contacts in the Australian aviation industry, and it is for this reason that there is a selection bias in the study respondents. No claim is made to suggest that the respondents in this survey are representative of any group in the aviation industry. The respondents represent themselves.

The survey questionnaire was designed to be neutral and contained no leading or biased questions. It was finalised after a trial with 10 aircrew. Eventually, 50 individuals from Australia returned completed surveys. Analysis of their surveys established similar findings to earlier studies (for example, see Table 1) with a moderate-sized group of respondents. Eighteen respondents returned questionnaires from North America — these were analysed separately.

In most cases it is not known whether the respondents' self-reporting was subjective or based on objective clinical or laboratory findings. This is a shortcoming of the survey. For example, the number of synonyms that exist for fatigue, that is, lack of energy, weakness, sleepiness, tiredness, lassitude, exhaustion, and so on, indicate the problems of assessing just one symptom.³⁸ In many cases, objective criteria exist for physicians to use in the diagnosis of such conditions. In some cases, respondents knew this and reported accordingly.

Patient diagnosis may also have been influenced by practice patterns in which their physicians specialised, that is, they reported symptoms diagnosed by specialists (not themselves). In other cases, agreement on case definitions of certain symptoms is not universal.³⁸ This overlap of symptoms and syndromes makes diagnosis complex.³³

Conclusion

The range of epidemiology studies varies, and the predictive power of each type of study varies depending on design and methodological, analytical and interpretational factors. This survey was a descriptive survey of a group of non-representational individuals who qualitatively described workplace exposure scenarios and self-reported symptoms from such exposures. For this reason, no attempt has been

made to ascribe causality or make inferences of a general nature. However, even with such procedural limitations, it was possible to draw a number of conclusions from this survey:

1. The hydraulics and lubricants used in the aviation industry contain a number of irritating and toxic ingredients.⁶
2. This study has shown that exposure to such contaminants, if they get into aircraft cabin air, can produce symptoms of toxicity.
3. The symptom clusters in aerotoxic syndrome can be described. These are:
 - symptoms of dysfunction in neurological function immediately after intense exposures, including loss of positional awareness, vertigo and loss of consciousness. If these symptoms occur in a pilot, they are a significant aviation safety problem;
 - symptoms of skin, eyes, nose and respiratory irritation immediately after exposure. Further exposures exacerbate the symptoms, often leading to other respiratory and cardiovascular effects;
 - symptoms of gastrointestinal discomfort immediately after exposure. While these recede with cessation of exposure, there is a suggestion that nausea and diarrhoea can persist;
 - some symptoms of impairment of neuropsychological function immediately after exposure, such as headache, dizziness, disorientation and intoxication. These symptoms become more debilitating after time, with problems of loss of cognitive function and memory problems emerging;
 - general symptoms of exhaustion progressing to chronic fatigue. It was common for respondents to spend layovers, weekends and holidays sleeping for days to overcome the symptoms of exhaustion; and
 - general symptoms of immune suppression developing some time after exposure, including food and alcohol intolerances, allergies and chemical sensitivity. These symptoms worsen with

continuing exposure and may worsen even after exposure ceases.

Where symptoms of discomfort, irritation or toxicity occur, this breaches airworthiness legislation.

4. Many surveys of workers report that working populations generally enjoy a higher level of health than the populations from which they arise. This is the “healthy worker” effect, a commonly observed phenomenon by which lower death rates (or injury or disease rates) are observed in workers relative to the general population.^{19,39} While this may be due to a selection bias problem, the aircrew in this survey had incidences of symptoms at much higher rates than population backgrounds — suggesting (in many cases) that they were unhealthier than the general population. However, as aircrew undergo regular health checks (pilots regularly, flight attendants less so), the levels of fitness and health in such individuals should be better than population norms.

5. There are a number of results from this study that require further investigation — particularly the findings of neurological impairment, respiratory system effects, reproductive dysfunction and other long-term effects.

Aerotoxic syndrome presents significant issues with regard to the health of pilots, cabin crew and passengers, but most notably with regard to air safety if pilots are incapacitated and cabin crew cannot supervise cabin evacuations during emergencies. Health effects include short-term irritant, skin, gastrointestinal, respiratory and nervous system effects, and long-term central nervous and immunological effects. Some of these effects are transient, others appear more permanent. The exacerbation of pre-existing health problems by toxic exposures is also highly probable.

There is also a hidden issue. Airline staff in Australia are worried about job security and what might happen to them if they complain about working conditions and make their symptoms public. This is especially apparent following the demise of a major Australian airline. At present, with only a few cases proceeding in

the courts, little compensation has been awarded to airline workers affected by toxic gases, vapours and fumes. Therefore, many crew are flying while further compromising their health and safety, and will only come forward when they become concerned that they may not be able to continue flying, or worse, when they are no longer able to fly.

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