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Research Article

The Effect of Flying and Low Humidity on the Admittance of the Tympanic Membrane and Middle Ear System

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ABSTRACT

Many passengers experience discomfort during flight because of the effect of low humidity on the skin, eyes, throat, and nose. In this physiological study, we have investigated whether flight and low humidity also affect the tympanic membrane. From previous studies, a decrease in admittance of the tympanic membrane through drying might be expected to affect the buffering capacity of the middle ear and to disrupt automatic pressure regulation. This investigation involved an observational study onboard an aircraft combined with experiments in an environmental chamber, where the humidity could be controlled but could not be made to be as low as during flight. For the flight study, there was a linear relationship between the peak compensated static admittance of the tympanic membrane and relative humidity with a constant of proportionality of 0.00315 mmho/% relative humidity. The low humidity at cruise altitude (minimum 22.7 %) was associated with a mean decrease in admittance of about 20 % compared with measures in the airport. From the chamber study, we further found that a mean decrease in relative humidity of 23.4 % led to a significant decrease in mean admittance by 0.11 mmho [$F(1,8)=18.95$, $P=0.002$], a decrease of 9.4 %. The order of magnitude for the effect of humidity was similar for the flight and environmental chamber studies. We conclude that admittance changes during flight were likely to have been caused by the low humidity in the aircraft cabin and that these changes may affect the automatic pressure regulation of the middle ear during descent.

Keywords: air travel, tympanic membrane, relative humidity, admittance, otic barotrauma, pressure regulation

INTRODUCTION

The health and comfort of the individuals onboard aircraft are affected by the environment created in modern airline cabins (see for example Brundret 2001; Nadga and Koontz 2003). The major difference between the air on an aircraft and that in ground transportation or buildings is that aircraft air is extremely dry. The optimal relative humidity for comfort is about 40 to 70 % (Rayman 1997), and the American Society of Heating, Refrigeration, and Conditioning Engineering standard for buildings (ASHRAE 1999) is for a minimum relative humidity of 20 %. The bleed air from the engines of a modern jet, which is used to maintain cabin pressure, has a relative humidity of 0.5 to 1 % (Space et al. 2000; Spengler and Wilson 2003), and most of the moisture within the cabin is provided by the passengers (Malmfors et al. 1989; O'Donnell et al. 1991), although there is also some moisture from galleys and toilets (O'Donnell et al. 1991). At cruise altitudes, the cabin humidity depends on passenger load (Malmfors et al. 1989; Arnold et al. 2000) and is typically 5 to 20 %, but can be as low as 2 % (Backman and Haghighat 2000; Wieslander et al. 2000). During take off and landing, the bleed air from the engines is shut off so that full power is available from the engines (Arnold et al. 2000; Lindgren 2003); in these periods, 100 % of the cabin air is re-circulated, and the humidity is therefore higher than at cruise altitudes, but is still low.

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Continued exposure to low humidity is known to lead to discomfort through drying of the skin and mucosal epithelia (Haugli et al. 1994; Spengler and Wilson 2003). At the end of a flight, particularly an international flight, most passengers and flight crew experience some effects of low humidity. Low humidity causes dryness of the throat (Wieslander et al. 2000; Nadga and Koontz 2003) and dryness and discomfort of the eyes (Backman and Haghighat 2000). Moreover, low humidity leads to discomfort through drying of mucosa in the nose (Lee et al. 2000; Space et al. 2000). Together, the eyes and nose are associated with the most common low-humidity symptoms for passengers and flight attendants (Haugli et al. 1994).

There are no direct reports of the effect of low humidity on the ear, which would suggest that immediate discomfort is non-existent or minor. Nonetheless, given that the tympanic membrane has an outer layer like skin (a keratinizing squamous epithelium) and an inner mucosal layer (Lim 1968), we considered that it may, like other epithelia, be susceptible to drying. As described below, this could be relevant to passenger comfort. Most walls of the middle ear are rigid except the pars flaccida and the pars tensa of the tympanic membrane (Shrapnell 1832), and the flexibility of the tympanic membrane therefore enables some buffering of pressure changes in the middle ear (Shrapnell 1832; Kanick and Doyle 2005). For example, when negative pressure starts to form in the middle ear, the more flexible pars flaccida retracts into the middle ear (Stenfors et al. 1979; Sadé 1997); this therefore reduces the volume of the middle ear and reduces the pressure difference. If the negative pressure persists after retraction of the pars flaccida, then the more rigid pars tensa will also start to retract (Stenfors et al. 1979; Sadé and Ar 1997; Decraemer and Dirckx 1998). The ability to compensate pressure, however, is limited to pressure changes less than ±200 daPa (Decraemer and Dirckx 1998). This passive regulation may be supplemented by the mastoid, which has a larger volume than the middle ear (Sadé and Ar 1997; Cinamon and Sadé 2003); those with a large mastoid have less risk of some chronic ear conditions such as chronic otitis media and cholesteatoma, and any episodes tend to be shorter (Sadé and Ar 1997), although, perhaps paradoxically, Sadé et al. (2003) report that adults predisposed to barotrauma have larger than average mastoids. Perhaps more important than passive regulation, the pars flaccida and pars tensa appear to be part of an active regulation system that detects the relative pressure in the middle ear (Rinaldi et al. 2013; Eden et al. 1990). The tympanic membrane is highly innervated (Lim 1968), and the subepidermal connective tissue and lamina propria of the human tympanic membrane contain mechanoreceptors similar to Pacinian corpuscles that seem to play an important role in sensing pressure (Nagai and Tono 1989). Anatomical evidence that these sensors are involved in active regulation comes from investigations that have shown neural connections between the tympanic plexus, the brainstem, and the Eustachian tube (Hecht et al. 1993; Rinaldi et al. 2013). There is also physiological evidence of active regulation mechanisms in that unilateral electric stimulation of the tympanic nerve in monkey has been shown to evoke bilateral electromyographic responses from Eustachian tube muscles (Eden et al. 1990). Moreover, Rockley and Hawke (1992) and Sakata et al. (2009) have shown that application of lidocaine hydrochloride to anesthetize the human tympanic membrane substantially increases the behavioural threshold for detecting pressure changes across the tympanic membrane.

If low humidity during flight dries the tympanic membrane, then this may be expected to decrease its peak compensated static admittance (hereafter shortened to admittance except when referring to details of the measurement); the buffering capacity of the tympanic membrane is therefore reduced. Furthermore, Sakata et al. (2009) have shown that decreasing the admittance of the pars tensa by the application of micropore tape led to a substantial increase in the threshold for detecting a change in pressure. With no tape applied, the mean admittance of ten participants was 0.88 mmho, and the thresholds for negative and positive pressures were −29 and 30 daPa, respectively. The application of one layer of tape decreased the mean admittance to 0.69 mmho and increased the negative and positive thresholds to −55 and 57 daPa, respectively. In other words, a 22 % change in the admittance was associated with nearly a 100 % increase in the pressure threshold. The addition of a second layer of tape decreased the mean further to 0.56 mmho and increased the negative and positive thresholds to −70 and 76 daPa, respectively. A decrease in the admittance of the tympanic membrane through flight might therefore be expected to directly affect the active regulation of middle ear pressure. Degradation of active regulation might be particularly relevant during aircraft descent as pressure changes in the middle ear commonly cause a painful retraction of the tympanic membrane known as otic barotrauma (Westerman et al. 1990).

To determine the effect of flight and low humidity on the tympanic membrane and middle ear system, we have carried out an observational study on an aircraft using tympanometry. Tympanometry enables measurement of the acoustic admittance of the ear canal, tympanic membrane and more medial middle ear system. We note, however, that the in-flight part of the study had many confounding factors. Repeated tympanometry measures, for example, are known to increase the admittance of the tympanic membrane through pre-conditioning (Gaihede 1996). We therefore supplemented the in-flight measurements with experiments in an environmental chamber where the humidity could be controlled. Nonetheless, the in-flight measurements gave an indication of the relationship between the acoustic admittance and the duration of flight. Furthermore, the in-flight study gave the opportunity to study the effect of humidities lower than those obtainable in an environmental chamber. Both parts of the study were approved by the Aston University Ethics Committee (Project 08/11).

METHODS

Experiment Onboard Aircraft

Ten healthy and otologically normal adult participants (seven males and three females) with no history of ear surgery or perforations took part in the in-flight study. The participants all had audiometric thresholds less than 20 dB HL at 500 Hz, 1 kHz, 2 kHz and 4 kHz, as measured using a GSI 61 Clinical Audiometer (Grason-Stadler Ltd). The participants flew specifically for the purpose of the study, and their flights and costs were supported by the study. The participants included the author (participant PF3), and a qualified audiologist (PF2); PF2 performed all the tympanometry in this study, including on herself, and all the otoscopy and pure-tone audiometry apart from on herself; this additional screening on PF2 was performed by another qualified audiologist who was otherwise not involved in the study. We included participants who sometimes developed otic barotrauma during flight, but for ethical considerations, this was subject to their meeting the following criteria: (1) any pain they had experienced through flying went away immediately after landing; (2) they flew regularly despite their predisposition to earache; and (3) they considered the pain to be tolerable. Of the participants recruited, six had never experienced barotrauma (PF2, PF6, PF7, PF8, P9, and PF10). The age range of the participants was 23 to 46 with a mean age of 32 years.

The ears of all participants were visually inspected using otoscopy a week before the first flight to ensure that there were no contraindications for performing tympanometry, e.g. excessive wax (British Society of Audiology 1992). Screening tympanometry measurements and measurements during flight were made with a portable Otowave 102–1 tympanometer (Amplivox Ltd). The probe tone used for measuring the peak compensated static admittance was at 226 Hz and 85 dB SPL, and the pressure range was from +200 to −400 daPa (pressure sweep from positive to negative). The tympanometer used automatic positive tail compensation, that is the admittance at 200 daPa, was automatically subtracted from the peak static admittance reading to compensate for the admittance of the ear canal volume. For a probe tone of 226 Hz, the admittance is almost entirely dominated by the compliance.

During screening, all the participants had tympanometry measures of ear canal volume, tympanometric peak pressure, and acoustic admittance within the normative values as defined by the British Society of Audiology (1992), i.e. ear canal volume between 0.63 and 1.46 cm^3, tympanometric peak pressure between −50 and 50 daPa, and acoustic admittance between 0.3 and 1.6 mmho.

Relative humidity has a negligible effect on the acoustic admittance of an enclosed volume of air, such as the external ear canal or a calibration cavity (Beranek 1954). The acoustic admittance depends, however, on the speed of sound in the medium and its density (for review see Lilly and Shanks 1981) both of which are pressure dependent. At lower pressure (greater altitude), the admittance of a fixed volume of air is higher, and a tympanometer calibrated at sea level will overestimate the ear canal volume. Since, however, the tympanometer used automatic positive tail compensation, the admittance measured in the plane of the probe tip, that is, the admittance of the tympanic membrane and middle ear system, will be largely unaffected by altitude. Calibration measures with a 0.5- and a 2-cm^3 cavity were taken throughout the flights, as time permitted. Calibration measures with the 0.5-cm^3 cavity showed no deviation on the ground or in either flight. Calibration measures with the 2-cm^3 cavity read 1.9 cm^3 on the ground with a mean of 2.1 cm^3 (N=4) during outbound level flight and 2.0 cm^3 (N=4) during level flight on the return journey.

The experiment was conducted on a Boeing 737 300/500 with the permission of the airline (British Midland Airways). As described below, the outward flight from Birmingham International in the United Kingdom to Palma in Spain was taken to be a pilot study. The participants stayed overnight in Palma and then returned to Birmingham International (take off 10:15 local time); the return flight lasted 2 h and 20 min. The participants were encouraged to be fully hydrated before and during the flight; bottled water was provided.

Temperature and relative humidity were measured using a Digitron 2080R hydrometer (Digitron Ltd.) typically every 10 min, but more often when workload permitted. The relative humidity measurements were accurate to 1.5 % over a range of 0 to 100 %, and the temperature measurements were accurate to 0.3 °C over a range of −10 to 50 °C. The airline requested that onboard equipment should be minimized. Therefore, to enable the flight status to be roughly gauged, ambient air pressure was measured using a ProTrek PRW-1300 watch (Casio Ltd.), which was nominally accurate to 100 Pa over a range of 2,600 to 11,000 Pa. Tympanometry measurements were made about every 20 min but, for logistical reasons, less frequently during take off and landing; at each measurement time, the participants were tested in a different random order. All equipment was approved by British Midlands Airways before the first experiment and by the captain.

Performing tympanometry in the cabin was more difficult than anticipated during the outbound flight, and it was difficult to get a good tympanometer seal with a fixed seating plan. Moreover, because of the confined space, the measurements were slow, and it sometimes took over 15 min to make the full set of measurements. The measurement time was exacerbated because it was often difficult to get an acceptable seal with participant PF6. To overcome these obstacles, several changes were made for the return flight. First, during the stay in Palma the participants were taught to make tympanometry measurements on themselves. Four of the participants (PF4, PF7, PF8, and PF10) were not able to do this and were therefore seated on aisle seats, or moved to an aisle seat during testing, so that the audiologist could make tympanometer measurements from behind the participant. To enable faster overall measurements on the return flight, no measurements were taken from participant PF6 (who may be considered a dropout). With these changes, a complete set of measurements took about 10 min on the return flight.

Experiments in Environmental Chamber

Nine participants (four males and five females) took part in the experiments in an environmental chamber in the School of Sport and Exercise Sciences at the University of Birmingham (UK); the participants included the author (participants PE4). The age range of the participants was 19 to 44 years old with a mean of 29. The participants included qualified audiologists who performed the measurements and screening. The inclusion and exclusion criteria were largely the same as for the aircraft study: participants were all otologically normal with audiometric thresholds less than 20 dB HL and had no history of ear surgery or perforations. We did not, however, exclude participants who might have experienced severe barotrauma because this ethical consideration was not relevant here. As for the in-flight experiments, the ears of all participants were visually inspected using otoscopy before the first session to ensure there were no contraindications for performing tympanometry. Two of the participants, PE3 and PE8, were known to have an admittance in one ear above 1.6 mmho, but this is not a contraindication for performing tympanometry, and we considered their participation to be safe.

Each participant took part in four sessions over 2 days. On each day, the participants were exposed in one session to a low relative humidity and in the other session to a normal relative humidity; each session lasted 2.5 h. Nominally, the low humidity condition as set by the environmental chamber was 20 %, but the actual mean humidity as measured using a recently calibrated Digitron 2080R hydrometer was 34.7 % (SD 2.3 %); this was the lowest humidity the environmental chamber could produce when occupied. For this low humidity condition, the environmental chamber was set to 20 % humidity (nominally) at least 2 h before the start of the session. The normal humidity condition was set to be 50 %, but the actual mean relative humidity was 58.1 % (SD 2.2 %). In the following two sessions, the order of the conditions was reversed, such that if the participant was exposed to low humidity in session 1 then they were exposed to the normal humidity condition in session 3 followed again by the low humidity condition in session 4. The participants were split into two groups such that one group started with the normal humidity condition in session 1 and the other with the low humidity condition. To simplify logistics, the first author, PE4, took part in all sessions. The conditions were approximately balanced, but the balance was broken because one potential participant dropped out from the first group. The logistics and costs of hiring the environmental chamber precluded changing the schedule to accommodate this potential participant or to replace them at short notice. In general, with the exception of participant PE1, the participants completed sessions 3 and 4 the day after the first two sessions.

In each session, the participants were relatively inactive within the chamber and generally read or watched a projected video. In both test conditions, participants were provided with bottled water and encouraged to drink freely. Participants were at liberty to leave the chamber during a session, but none did. Tympanometric measures were made every 30 min using a GSI-38 tympanometer (Grayson Stadler Ltd). As for the in-flight study, the tympanometer measured the peak compensated static acoustic admittance with a probe tone of 226 Hz. At each measurement interval, the participants were tested in a different random order. At each measurement interval, the relative humidity and temperature were also recorded using a Digitron 2080R hydrometer, as for the flight experiments.

RESULTS

Experiment Onboard Aircraft

The cabin environment for the flight from Palma to Birmingham International is shown in Figure 1. The relative humidity decreased substantially during the course of the flight. The relative humidity of 51.6 % during embarkation was approximately the same as the mean relative humidity in the departure lounge (45.6 % and SD 1.0 % for five measurements taken approximately 5 min apart). After take off, the relative humidity decreased continuously and substantially during the course of the flight to a minimum of 22.7 %. About 20 min before landing, presumably when the air was 100 % re-circulated, the relative humidity increased again and was 35.2 % on landing. The cabin temperature of the aircraft following embarkation was 27.5 °C and, after an initial increase to 32.1 °C during the first 20 min, it decreased gradually during the remainder of the flight (mean 27.2 °C SD 2.3 °C).

The effect of flight on the admittance of the tympanic membrane and middle ear system for nine of the participants is shown in Figure 2; as described in the "Methods" section, no measurements were taken from PF6. We also failed to obtain an appropriate seal for the left ear of PF5; moreover, we stopped recording from the right ear of PF5 about 2 h after embarkation because the participant was experiencing moderate discomfort. This started during level flight and was therefore more likely to have been caused by repeated insertion of the tympanometer probe than by otic barotrauma. We also failed to get a right-ear seal for PF7 134 min after embarkation. The individual data are considerably variable both across participants and between measurement intervals. There was nonetheless a tendency for the admittance in the individual data to decrease in the middle of each flight, when the relative humidity was lowest.

The overall effect of flight on admittance is shown more clearly in Figure 3, which displays mean values across the participants. The airport measurements appear to be continuations of the onboard measurements made immediately after embarking and immediately before disembarking. For both ears, the admittance gradually decreased during the flight but increased again towards the end of the flight as the aircraft descended. The change in admittance corresponded with the change in relative humidity, which is shown by the dashed line in Figure 3; as described above, the humidity in the aircraft increased during descent, presumably because the air was 100 % re-circulated.

The mean right ear measurement made 134 min after embarkation is discontinuous from the other measurements; this measurement was made just as the aircraft started to descend and the change in pressure may have interfered with the tympanometry. This data point appears as an outlier in Figure 4, which shows the relationship between the mean admittance across participants at each measurement time and the relative humidity. The data are shown separately for left ear measurements (blue left-pointing triangles) and right-ear measurements (red right-pointing triangles) and include measurements made in flight and in the departure and arrival lounges. Over the range of relative humidities experienced (22.7 to 66.3 %), the relationship between the admittance and humidity was linear. Pearson's r correlation coefficients were moderately high and statistically significant for both the left [$r(17)=+0.720$, $P=0.001$] and right ears [$r(17)=+0.810$, $P<0.001$]; these analyses exclude the outlier for the right ear 134 min after embarkation and, for consistency, the corresponding mean measurement from the left ear (shown by a blue asterisk in Figure 4 at a relative humidity of 26.4 % that is obscured by other data points). The relationships between humidity and admittance were similar for the two ears, and the data were therefore averaged by taking the arithmetic mean at each measurement interval. The Pearson's r for the combined data was high and significant [$r(17)=+0.813$, $P<0.001$], and the least-squares best-fit line had a gradient of 0.00315 mmho/% relative humidity. As shown in Figure 4, a change in

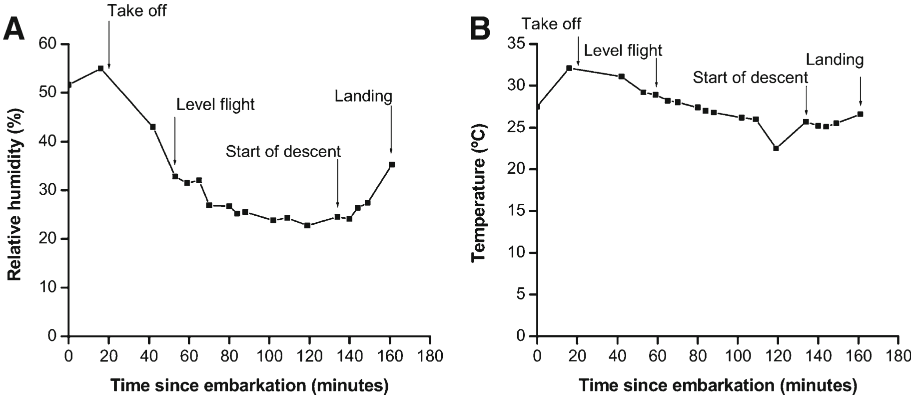

FIG. 1. Plots of **A** humidity and **B** temperature during the flight. *Arrows* show the various stages of flight.

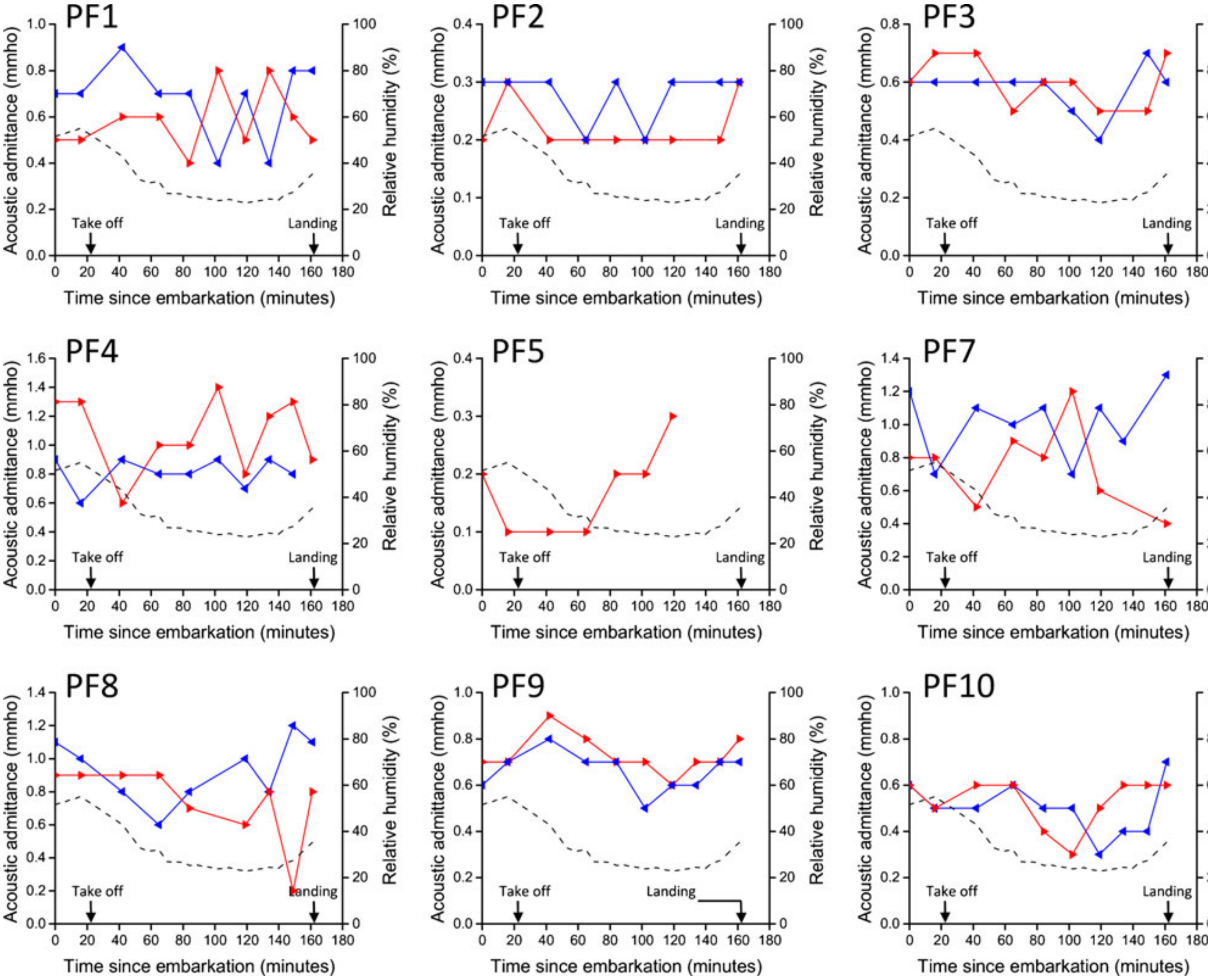

FIG. 2. Effect of flight on the acoustic admittance of the middle ear for individual participants. Each plot shows the admittance of the left ear (*blue left-pointing triangles*) and right ear (*red right-pointing triangles*) against the time after embarkation. The take off and landing times are shown by *arrows*. The *dashed black solid lines* show the relative humidity during the flight. For participant PF5, it was not possible to get a tympanometer seal for the left ear, and recording from the right ear was discontinued 2 h after embarkation because of ear discomfort. For participant PF7, it was generally difficult to get a tympanometer seal for the right ear and not possible in the measurement period 134 min after embarkation (see main text). PF6 dropped out after the pilot study (outward flight).

relative humidity of about 40 % was associated with a change in the mean admittance of about 20 %.

Experiments in Environmental Chamber

The humidity in the environmental chamber for the normal and low humidity conditions was approximately constant both within sessions and across sessions with the same humidity condition: in the normal humidity condition, the standard deviation of the relative humidity was 2.2 % (mean 58.1 %), and in the low humidity condition, the standard deviation was 2.3 % (mean 34.7 %). The temperature was a constant 23.0 °C across all sessions and conditions.

For both ears of the nine participants, the mean middle-ear admittance over the whole session (0 to 150 min) was almost always lower in the low- than in the normal-humidity condition (Fig. 5), if only marginally; the only exception was for the right ear of participant PE7, where the admittance in the low humidity condition was marginally higher. For participants PE3 and PE8, whose left-ear admittances were above the normative values defined by the British Society of Audiology (1992), the relative change in admittance between the two humidity conditions was about the same as for the other participants.

As shown in Figure 6, any change in admittance during a session occurred within about 30 min of the

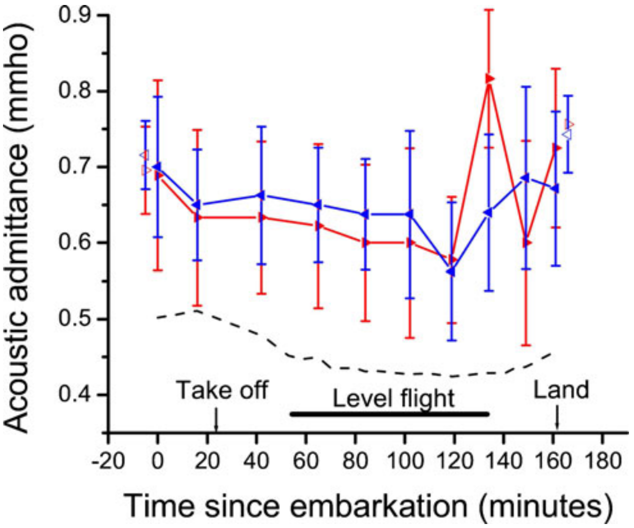

FIG. 3. The mean acoustic admittance of the left (*solid blue left-pointing triangles*) and right (*solid red right-pointing triangles*) ears during flight as a function of time after embarkation. The *error bars* show the standard error of the mean. The *dashed line* shows the relative humidity as a function of time since embarkation. The humidity is shown with an arbitrary offset and scaling and has been included to enable a visual comparison between changes in humidity and changes in acoustic admittance; actual values of the humidity are shown in Figure 1. The *open triangles at the left and right side* of the figure show, respectively, the mean pre-flight and post-flight acoustic admittance that were measured in the terminal buildings for left ears (*blue*) and right ears (*red*). Take off was 21 min after embarkation, and landing was 161 min after embarkation.

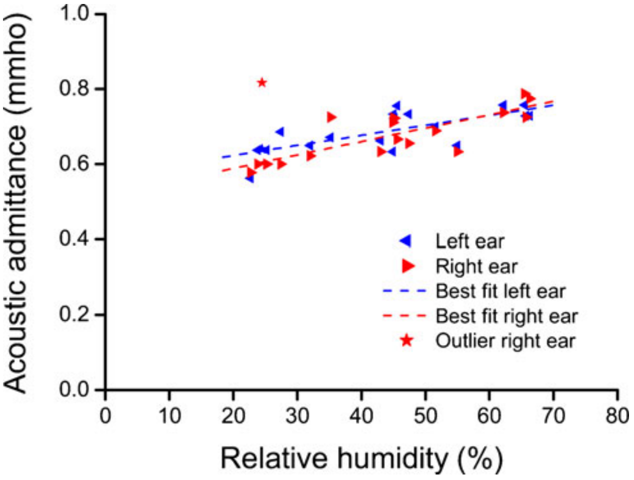

FIG. 4. Relationship between the mean acoustic admittance across participants and the humidity during flight. The figure includes measurements made in the departure lounge, the flight, and the arrival lounge. Measurement of the mean acoustic admittance for the left ears is shown by the *blue left-pointing triangles*, and those from right ears are shown by the *red right-pointing triangles*. The outlier marked by the *red asterisk* was from right-ear measurements made at the start of descent. The *blue and red lines* show the least-squares fit to the left and right ear data, respectively, and exclude the outlier and the corresponding measurement from the left ear.

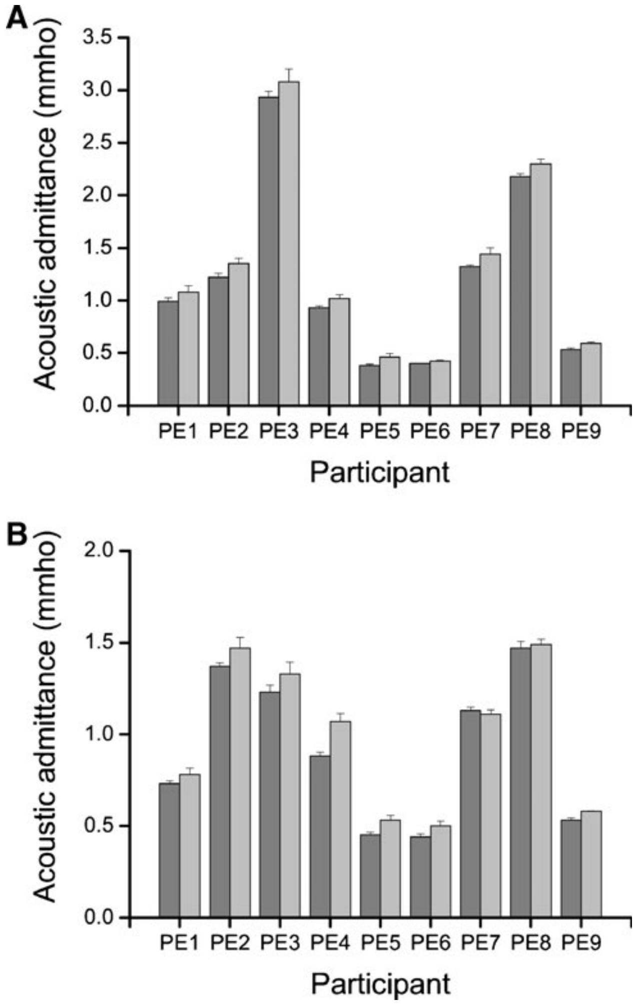

FIG. 5. The effect of humidity on the acoustic admittance of the left ear (**A**) and right ear (**B**) for individual participants. The *dark grey bars* show the acoustic admittance for the low humidity condition, and the *light grey bars* show the acoustic admittance for the normal humidity condition. *Errors bars* show the standard error of the mean.

start of the session. The initial admittances for both conditions appear more similar to those in the steady-state low-humidity condition. The initial conditions will have depended on the outside relative humidity and the effect of air conditioning in the building and ante-chamber; the humidity in the building and ante-chamber was not measured. It is likely that the humidity in the low-humidity condition was more similar to the humidity in the rest of the building rather than the outside humidity. The mean relative humidity of 58.1 % in the normal-humidity group is fairly typical for relative humidity outside in the UK.

To determine the steady-state effect of humidity on admittance, an analysis was performed on the last four measurements from each session (60 to 150 min inclusive). A repeated-measures ANOVA with humidity (low/high), ear (left/right), session (first/second), and measurement time (60, 90 min, etc.) as main

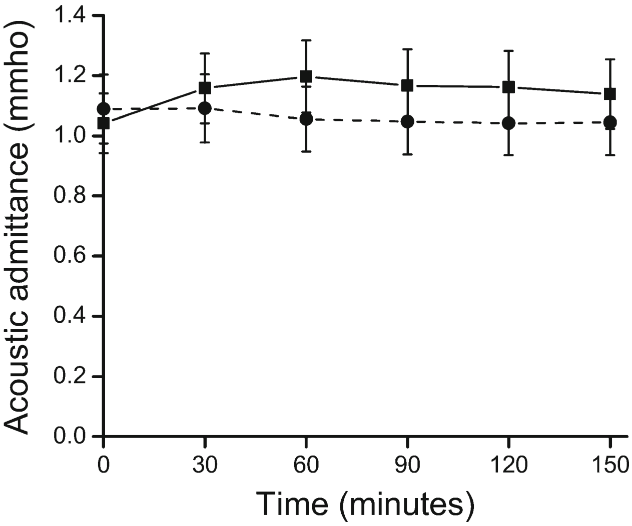

FIG. 6. The mean acoustic admittance of the tympanic membrane for participants exposed to a normal humidity (*solid line*) or a low humidity (*dashed line*). *Errors bars* show the inter-participant standard error of the mean.

factors showed that the humidity condition had a significant effect on admittance [$F(1,8)=18.95$, $P=0.002$]. There was no significant difference between ears [$F(1,8)=2.39$, $P=0.161$], session [$F(1,8)=3.27$, $P=0.108$], or measurement time [$F(3,25)=1.80$, $P=0.174$] and no significant interactions. The mean admittance for the low humidity condition was 1.05 mmho over all ears, sessions, and measurement times (standard error 0.20 mmho). The corresponding mean admittance for the normal humidity condition was 1.16 mmho (standard error 0.22 mmho). A mean change in relative humidity of about 23.4 % therefore led to a change in mean admittance of 0.11 mmho (a decrease of 9.4 %).

DISCUSSION

The time course of the humidity during the flight, which was lowest at cruising altitude, was typical of those previously measured (Haghighat et al. 1999; Lindgren 2003) and consistent with theoretical predictions (Arnold et al. 2000). The minimum humidity of 22.7 % during the flight is higher than many maximum humidity measurements for other flights, such as those by O'Donnell et al. (1991), Haghighat et al. (1999), Lee et al. (1999), and Lindgren (2003). A contributing factor to the relatively high humidity on the flight in this study may have been the relatively high temperatures, which had a mean of 27.2 °C. These temperatures are higher than that found in any aircraft by Haghighat et al. (1999) and more than the mean value found by O'Donnell et al. (1991). Given that most of the moisture in the cabin is from perspiration of the passengers (O'Donnell et al. 1991; Arnold et al. 2000) the high temperatures on the flight may have led to relatively higher humidity through greater perspiration.

Despite the smaller than expected changes in humidity on the aircraft, there was a change in the tympanometer reading for admittance during the flight, and the admittance reading was strongly correlated with the relative humidity ($r=0.831$). As previously described, the observational study was confounded by the effect of multiple measurements on admittance. Nonetheless, the evidence that humidity affects the admittance during flight is more compelling because the admittance increased as the humidity increased during descent. This evidence alone, however, is not conclusive. During ascent and descent, passengers will make more pressure equilibrations through Eustachian tube openings. Such pressure equilibrations will be preceded by a positive or negative pressure load on the tympanic membrane, which is similar to the pressure loading during tympanometry. The admittance might be expected to increase after a pressure load has been released just as admittance increases following tympanometer preconditioning (Gaihede 1996). It is notable in Figure 3, however, that the mean admittance appeared to decrease during ascent and level flight, in other words opposite to the direction expected from pressure loading. We also note that the study within the environmental chamber, which controlled for preconditioning and any pressure loads before Eustachian tube opening, showed that humidity did have a significant effect on admittance reading. Moreover, the order of magnitude of this effect was the same for the flight and for the environmental chamber experiments: in the environmental chamber, a mean change in relative humidity of 23.4 % led to a mean change of the admittance reading of 0.11 mmho, whilst on the aircraft, a change in relative humidity of 23.4 % led to an increase of 0.063 mmho (based on the gradient of the regression line).

The change in the admittance may have resulted from changes to the mass or compliance of the tympanic membrane and middle ear system. If the effect of flight was to increase the mass of the tympanic membrane or middle ear system, then this would also have led to a decrease in the admittance. Because, however, the probe frequency of 226 Hz was low compared with the resonant frequency of the middle ear, changes in mass would be expected to make negligible difference to the admittance at the probe frequency (Lilly and Shanks 1981); moreover, lower humidity would be expected to be associated with greater evaporation, and we therefore consider it unlikely that it would have led to greater mass. Nonetheless, multi-frequency tympanometry would be required to confirm the assumption that the changes in admittance were indeed compliance dominated.

Tympanometry cannot distinguish between admittance changes associated with the tympanic membrane and those associated with the middle ear system. Given, however, that the tympanic membrane was immediately adjacent to a region of low humidity in the external ear, we consider it more likely that humidity affected the admittance of the membrane rather the more medial middle ear system. Moreover, the "air" in the middle ear normally has a relative humidity of nearly 100 %, and the tympanic membrane is relatively impervious to gas diffusion across it (Yuksel et al. 2009).

CONCLUSIONS

During the flight, where the minimum relative humidity was 22.7 %, the change in humidity over the course of the flight was associated with a relative change in the admittance of about 20 %. For more typical flights, where the relative humidity is lower, even higher percentage changes in the admittance might be expected. The observed admittance changes are quite substantial as relative changes, but they are modest compared with the absolute range of admittances in the general population: the normative range (5 to 95 %) in younger adults is about 0.3 to 1.4 mmho (Margolis and Heller 1987). If low humidity is a factor in the incidence and severity of otic barotrauma, then it must be the relative change that is consequential. Given that, as described earlier, the normal flexibility of the tympanic membrane enables only small pressure changes to be buffered and the pressure change during descent is much larger, a 20 % change in the buffering capacity of the tympanic membrane is unlikely to be clinically important. The 20 % changes in admittance, however, are similar to the 22 % change in admittance that Sakata et al. (2009) observed when they applied a single layer of micropore tape to the pars tensa; in Sakata et al's study, this admittance change was associated with nearly a 100 % increase in the behavioural pressure threshold. The change in admittance caused by low humidity during flight may therefore substantially disrupt the pressure sensing mechanisms in the tympanic membrane and therefore disrupt the automatic pressure regulation of the middle ear, although this may be partially mitigated by mechanoreceptors in the middle ear cavity (Lim et al. 1975). Further study is required to determine whether humidity affects the behavioural pressure threshold. If active regulation is disrupted, then it becomes more important that passengers take conscious steps to equalize pressure in the middle ear, such as performing Valsalva's manoeuvre.

The participants in this study, for both the flight and environmental chamber experiments, were encouraged to drink freely, so it appears that simply maintaining hydration of the whole body is insufficient to maintain the admittance of the middle ear.

Given that low humidity is known to cause discomfort to the skin, eyes and nose, and may affect the ears, it would be desirable from a health perspective to humidify the cabin. It is notable that the cockpits of many commercial aircraft do have humidified air (Lindgren 2003) and double-blind tests of humidification in the cabin led to the perception of fresher and less dry air (Lindgren et al. 2007). Several arguments, however, are given for the low humidity in the aircraft cabin. First, having a relative humidity above 25 % is purportedly precluded by the effects of condensation, corrosion and fatigue of the aircraft structure (Haghighat et al. 1999; Grün et al. 2012). In terms of condensation, even with very low relative humidity the weight of an aircraft increases by several hundred kilograms at cruise altitude because of cold wall condensation; the provision of higher humidity would increase this weight further. Second, low cabin humidity purportedly lowers the levels of bacteria, moulds and fungi (Space et al. 2000), although in an experiment by Norbäck et al. (2006) where the humidity was raised by 3 to 10 % the levels of bacteria and moulds were reduced by 50 to 80 %. Third, it is considered prohibitively expensive to carry sufficient water at take off to make a substantial difference to the relative humidity (Spengler and Wilson 2003).

If higher humidity in the cabin is not possible, it may be beneficial to artificially apply moisture to the ear. In the introduction of a study on the use of pseudoephedrine to prevent otic barotrauma, Buchanan et al. (1999) note that the application of a warm wet towel over the external ear has been commonly advocated to "decrease the ambient pressure"; there is no evidence that this method works, but the effect of the wet towel might actually be to increase the admittance of the tympanic membrane. The approach reported by Buchanan et al. is similar to an approach used by some flight attendants whereby moistened napkins or cotton wool are put in a cup that is then put over the ear. To our knowledge, there is no description of this method in the scientific literature, and again no evidence that it works, but it appears to be common practice among flight attendants given the number of websites that mention this approach; an interesting area for further study would be to determine whether this approach reduces the incidence or severity of otic barotrauma.

We finally note that the observed change in middle ear admittance with humidity may be relevant to the clinical diagnosis of middle ear defects using tympanometry. As an extreme example of the effect of pressure on acoustic impedance, Lily and Shanks (1981) considered two locations: Long Beach, California (elevation 22 m) and Santa Fe, New Mexico (elevation 2,138 m). Their calculations showed that the pressure difference between the two locations would lead to a 23 % difference in the measured admittance. The mean afternoon relative humidity in June in Long Beach is 67 %, whilst the comparable mean in Santa Fe is 18 %. This range of humidities is comparable to that observed on the aircraft, which was associated with a change in middle ear admittance of about 20 %. Our results therefore suggest that the humidity difference between locations should also be considered when interpreting normative data.

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