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Relation between temporal bone pneumatisation and middle-ear barotrauma in aircrew members

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Main Article

Dr A Hussein takes responsibility for the integrity of the content of the paper

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Abstract

Objective. This study aimed to assess the potential role of pneumatisation of the mastoid and its communicating air cells in the development of middle-ear barotrauma in aircrew members.
Methods. Seventy-nine aircrew members (158 ears) underwent temporal computed tomography. All were assessed before flying by clinical examination and audiology evaluation, followed by post-flight examination to detect barotrauma.
Results. Aircrew members' ears were divided into 3 groups based on barotrauma and temporal bone pneumatisation: 33 ears with barotrauma and temporal bone pneumatisation of 71 cm^3 or greater (group A); 12 ears with barotrauma and temporal bone pneumatisation of 11.2 cm^3 or lower (group B); and 113 ears with no barotrauma (group C). Mean pneumatisation volumes were 91.05 cm^3, 5.45 cm^3 and 28.01 cm^3 in groups A, B and C, respectively. A direct relationship was observed between volume of temporal bone pneumatisation of 71 cm^3 or greater and barotrauma grade.
Conclusion. Pneumatisation volume of the mastoid and its communicating air cells that ranges from 11.3 cm^3 to 70.4 cm^3 serves as a reliable predictor of the avoidance of middle-ear barotrauma associated with flying in aircrew members who have normal resting middle-ear pressure and good Eustachian tube function.

Introduction

Modern air travel exposes aircrew to rapidly changing ambient pressures, which consequently affects the middle-ear cavity, one of the air-containing cavities of the body.[1] Otitic barotrauma is a traumatic inflammation of the middle ear induced by the difference in pressure between the middle ear and the surrounding environment.[2] Barotrauma is considered to be the most frequent medical problem related to aeroplane travel and has been mentioned as a causal element in aviation accidents.[3] Difficulty in equalising middle-ear pressure with ambient pressure during flight is a common cause of the temporary or permanent grounding of an aircrew.[4]

Temporal bone pneumatisation may be divided into primary and accessory regions: the primary region, which consists of the middle ear, squamomastoid (mastoid) area, perilabyrinthine and petrous apex; and the accessory region, which consists of the squamous and the zygomatico-occipital parts.[5] As part of the primary region, the middle ear consists of two functionally distinct but continuous air spaces: the anterior tympanum and the posterior mastoid cavity, which is subdivided into numerous intercommunicating air cells.[6] The anterior wall of the tympanum is continuous with the osseous portion of the Eustachian tube, and the posterior wall opens to the mastoid air space by way of a large air cell, the antrum.[6] While variance in the volume of the tympanum among different individuals and age groups is low, that of the mastoid is large because of many factors, such as age, gender and disease history effects.[7]

During an aeroplane's ascent to high altitudes, the pressure in its cabin decreases and the air in the middle ear of those aboard expands; this is followed by a passive escape of middle-ear air through the Eustachian tubes and an equalisation of ambient pressure with middle-ear pressure.[8] The process of passive venting happens in a differential pressure of 15 mmHg, at every 400–500 feet (122–152 m) of ascent.[9] During descent, the ambient pressure rises, while the pressure in the middle ear becomes negative relative to the ambient pressure. Thus, the air cannot passively re-enter the Eustachian tube, and the Eustachian tube must be actively opened to equilibrate the pressure on both sides of the tympanic membrane; if this fails to occur, barotrauma develops.[10]

Uzun *et al.*[11] reported an inverse relationship between the size of pneumatisation and the risk of middle-ear barotrauma in sport scuba divers. Differentially, a low frequency of barotrauma was reported in ears that had poor Eustachian tube function in combination with a hypermobile tympanic membrane and small mastoid.[12]

In contrast to the role of mastoid pneumatisation in regulating middle-ear pressure, it has been reported that in patients with normal tympanic membranes and no history of

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recurrent or chronic otitis media, the amount of mastoid pneumatisation likely represents a normal distribution of organ size variation and is not related to the ability to equalise pressure in the middle ear.[13]

In our review of the literature, we found one study, by Sade *et al.*,[12] that assessed the relationship between mastoid pneumatisation and middle-ear barotrauma associated with flying in chronic ear disease patients. We found no previous research that examined such a relationship in patients with healthy ears. Therefore, this study was conducted to assess the potential role of pneumatisation of the mastoid and its communicating air cells within the temporal bone in the development of middle-ear barotrauma in aircrew members.

Materials and methods

A prospective cohort study was conducted at Saudi Airlines Medical Services from August 2014 to October 2018 on 79 aircrew members who underwent computed tomography (CT) scanning of the temporal bone for medical conditions such as tinnitus and/or headache. Patients were invited to participate in the study, and those who agreed to take part provided fully informed consent. Patients were given a full ENT examination and nasal endoscopy to examine the nose and Eustachian tube area.

Audiology assessment before flying was performed by an audiologist (author NE), who measured resting middle-ear pressure using a tympanometer (GSI Tympstar version 2; Grason-Stadler, Eden Prairie, Minneapolis, USA). In addition, a nine-step inflation–deflation test was performed, according to the method described by Bluestone and Cantekin,[14] to assess Eustachian tube function. All aircrew members must be deemed fit to fly before a flight, by exhibiting a resting middle-ear pressure that ranges from −55 to + 50 millimetres of water (mmH_2O), and tympanic membrane compliance within the range of 0.3 to 1.5 millimhos, and by passing the nine-step inflation–deflation test as recommended by the first author (AH) in a previous study.[4]

Aircrew members were excluded from the study if they had used 100 per cent oxygen during a flight (which predisposes to barotrauma), had a marked deviated septum, an upper respiratory tract infection before flying, or had a history of: previous nose or ear surgery; a nasal mass; polyps; uncontrolled allergic rhinitis; a perforated, scarred or flaccid tympanic membrane; and cholesteatoma or any middle-ear lesions.

Flights of all aircrew members were made in aircraft of a similar type (Airbus), and were similar in terms of maximum altitude (approximately 25 000–30 000 feet (7620–9144 m)) and rate of descent (400–500 feet (122–152 m) per minute). All flights were round-trip, one-leg flights (i.e. only one destination with a return back); the outward and return flights both took place on the same day for all aircrew members.

All aircrew members were assessed by the first author (AH) on the day of the return flight. The observer of barotrauma (AH) was blinded to the temporal bone pneumatisation findings on CT scans. Hence, there was no prior knowledge of the degree of pneumatisation in the examined aircrew members, in order to decrease observer bias. Each ear of individual aircrew members was assessed separately by clinical examination to detect the presence and grade of barotrauma (according to Teed's classification[15]), as follows: grade 0 – feeling of a blocked ear with pain, but with a normal otoscopic picture; grade 1 – presence of retraction, with redness in Shrapnell's membrane and along the manubrium; grade 2 – presence of retraction, with redness of the entire eardrum; grade 3 – same as grade 2 plus fluid in the tympanum or haemotympanum; and grade 4 – findings indicative of eardrum perforation.

Temporal bone pneumatisation measurement

In the current study, temporal bone pneumatisation refers to pneumatisation of the mastoid bone and its communicating air cells within the temporal bone. Temporal bone CT scanning was carried out using an Optima CT 660 scanner (General Electric, Waukesha, Wisconsin, USA).

The radiologist (author NF) measured the volume of mastoid air cells and cells communicating with the mastoid within the temporal bone on CT axial two-dimensional images, with 1 mm slice thickness, using the adult protocol (scanner settings of: 120 kV, 60/100 mAs, collimation = 0.75 mm), with appropriate multi-planar reconstruction in all cases. Volume was determined using the 'Paint on Slice' tool available with our institute's CT machine. This tool is used to automatically calculate the volume of the structure of interest after manually defining its contour.

The contour of the mastoid air cells was defined manually in all axial CT slices containing a part of it. Edge attraction was also used, which automatically refines the drawn contours by adjusting them to the nearby edges. The contour of the mastoid communicating cells was edited using the expansion 'add' tool; the contour is manually extended at the selected images to include the desired regions. Finally, the contour is updated to include the mastoid air cells and the cells communicating with the mastoid within the temporal bone.

As the radiologist was blinded to the ear barotrauma data, there was no prior knowledge regarding barotrauma in the examined aircrews, in order to decrease observer bias. Data on barotrauma of each ear for all patients, and on volume of temporal bone pneumatisation in the same ear, were sent to a statistician to correlate the incidence and degree of barotrauma to the measurement of temporal bone pneumatisation volume.

Statistical analysis

Data on temporal bone pneumatisation volume, and on presence and grade of barotrauma, in all groups, were calculated, tabulated and statistically analysed. Statistical analysis was conducted using SPSS software version 17 for Windows (SPSS, Chicago, Illinois, USA). *P*-values were considered significant if less than 0.05.

Results

The study was performed on 79 aircrew members (45 males and 34 females) (total of 158 ears), with ages ranging from 24 to 57 years (mean = 38.5 years).

Middle-ear barotrauma was detected in 45 ears, or 28.4 per cent of all ears in the study. Three of the 79 aircrew members (3.8 per cent) had asymmetrical pneumatisation of the mastoid. Ears of the aircrew members were divided into 3 groups based on barotrauma and temporal bone pneumatisation: group A included 33 ears with barotrauma and temporal bone pneumatisation of 71 cm^3 or greater; group B included 12 ears with barotrauma and temporal bone pneumatisation 11.2 cm^3 or lower; and group C included 113 ears with no barotrauma.

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Table 1. Temporal bone pneumatisation volume for all groups

Group	Minimum	Maximum	Median	Mean ± SD
A	71.00	116.00	88.10	91.05 ± 12.28
B	1.10	11.20	4.45	5.45 ± 3.98
C	11.30	70.40	22.70	28.01 ± 15.51

Data represent temporal bone pneumatisation volume, in cm^3. SD = standard deviation

Temporal bone pneumatisation volume ranged from: 71–116 cm^3 in group A (median = 88.10 cm^3, mean (± standard deviation) = 91.05 ± 12.28 cm^3); 1.1–11.2 cm^3 in group B (median = 4.45 cm^3, mean = 5.45 ± 3.98 cm^3); and 11.3–70.4 cm^3 in group C (median = 22.7 cm^3, mean = 28.01 ± 15.51 cm^3) (Table 1).

A significant difference ($p < 0.001$) was detected in mean temporal bone pneumatisation volume between pneumatised patients in group A (temporal bone pneumatisation ≥ 71 cm^3 with barotrauma) and patients with no barotrauma (group C) (Table 2). In addition, a significant difference ($p < 0.001$) was detected in the mean temporal bone pneumatisation volume between pneumatised patients in group B (temporal bone pneumatisation ≤ 11.2 cm^3 with barotrauma) and patients with no barotrauma (group C) (Table 3).

In group A, there was a statistically significant correlation ($p < 0.001$) between the degree of temporal bone pneumatisation and the extent of barotrauma (Table 4). In group B, however, no statistically significant correlation was seen between the degree of temporal bone pneumatisation and the extent of barotrauma ($p = 0.63$; Table 5).

Table 2. Difference in mean temporal bone pneumatisation volume between groups A and C*

Group	Mean ± SD	Mean difference	*P*-value
A	91.05 ± 12.28	63.04	<0.001
C	28.01 ± 15.51		

Data represent temporal bone pneumatisation volume, in cm^3, unless indicated otherwise. *Significance determined using the independent sample *t*-test. SD = standard deviation

Table 3. Difference in mean temporal bone pneumatisation volume between groups B and C*

Group	Mean ± SD	Mean difference	*P*-value
B	5.45 ± 3.97	22.56	<0.001
C	28.01 ± 15.51		

Data represent temporal bone pneumatisation volume, in cm^3, unless indicated otherwise. *Significance determined using the independent sample *t*-test. SD = standard deviation

Table 4. Relation between temporal bone pneumatisation volume and barotrauma grade in group A*

Barotrauma grade	Ears (*n*)	Pneumatisation volume (mean ± SD; cm^3)	*P*-value
1	9	78.93 ± 4.32	<0.001
2	11	87.06 ± 6.89	
3	13	102.82 ± 8.69	

*Significance determined using the analysis of variance test. SD = standard deviation

Discussion

In modern aviation, the cabin is pressurised at cruising altitudes to raise air pressure to three-quarters (570 mmHg) of the ground atmospheric pressure (760 mmHg).[16] Consequently, during air travel, people are exposed to a pressure variation of 190 mmHg during take-off and landing.[4]

The physiological pathways for the regulation of middle-ear pressure are as follows: tympanum–antrum–mastoid; middle ear–middle-ear mucosa–blood; and tympanum–Eustachian tube–nasopharynx.[17] In a normal population, the total volume of mastoid air cells is variable, and is approximately 20 times larger than the volume of the middle-ear cavity.[11] Because the tympanum and mastoid are continuous air spaces, total pressure differentials are rapidly equilibrated, and gas partial-pressure differentials disappear quickly.[17]

Gas exchange between the middle ear and the blood by the middle-ear mucosa depends on gas diffusion at a rate of 0.0008 mmHg/minute.[18] This means that during approximately 20 minutes of taking off or landing, the pathway is expected to buffer approximately 0.0160 mmHg. Consequently, this pathway has a minimal effect on middle-ear pressure regulation when the ambient pressure changes during descent and ascent in flying. The remaining pathways of pressure regulation, therefore, are through the Eustachian tube and mastoid air cell–mastoid mucosa–blood.

In the current study, all aircrew members had normal resting middle-ear pressure and good Eustachian tube function, as assessed with the nine-step test, thus allowing investigation of the other potential means of middle-ear pressure regulation (when flying) through the mastoid bone and its communicating air cells.

In literature reviews, most studies on the relationship between mastoid pneumatisation and barotrauma were conducted in diving[11] or submarine[13] situations, and X-rays were used to measure mastoid pneumatisation. The measurement of mastoid air cell volume with X-rays, by either the planimetric or rectangular method, is, in our opinion, inaccurate. In our study, we found CT scanning to be a more accurate method because it measures volume using the 'Paint on Slice' tool in CT axial images with a 1 mm slice thickness, which seems logical in the actual measurement of air cells.

In the literature, extensive intercommunications have been reported between the five areas of temporal bone pneumatisation; namely, the middle ear, mastoid, perilabyrinthine, petrous apex and accessory regions.[19] Thus, in the current study, we not only measured the volume of the mastoid air cells but also the mastoid communicating air cells within the temporal bone. This seems appropriate given that mastoid air cells and mastoid communicating air cells are continuous air space chambers that experience rapid equilibration of total pressure differentials. To our knowledge, the current study is the first to investigate the effect of temporal bone pneumatisation by using CT scanning to observe the development of barotrauma in aircrew members.

Uzun *et al.*[11] reported an inverse relationship between the size of mastoid pneumatisation and middle-ear barotrauma in sport scuba divers with no barotrauma, in ears with a mastoid pneumatisation of greater than 34.7 cm^2. Conversely, in the current study, we detected a direct relationship between the size of temporal bone pneumatisation and middle-ear barotrauma in all ears with temporal bone pneumatisation of greater than 71 cm^3 in aircrew members. This is because strict criteria were used in our study to assess aircrew fitness before flying, and CT scanning was employed to determine

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Table 5. Relation between temporal bone pneumatisation volume and barotrauma grade in group B*

Barotrauma grade	Ears (*n*)	Pneumatisation volume (mean ± SD; cm^3)	Mean difference (cm^3)	*P*-value
1	8	5.86 ± 4.21	1.24	0.63
2	4	4.63 ± 3.92		

*Significance determined using the independent sample *t*-test. SD = standard deviation

pneumatisation of the mastoid and its communicating air cells. Uzun and colleagues only used tympanometry to assess fitness before diving, and utilised X-rays to assess mastoid pneumatisation alone, without concomitant assessment of the air cells communicating with the mastoid.

In the present study, we found that the greater the volume of temporal bone pneumatisation, the greater the degree of barotrauma. Regarding the equalisation of middle-ear pressure (during flight) via the Eustachian tube, according to Boyle's law, a larger volume change is expected to occur in an ear with large pneumatisation (large volume) – which would, in turn, produce an associated greater burden on the Eustachian tube to equalise the pressure – than in an ear with small mastoid volume. Consequently, an ear with a large volume may be more vulnerable to barotrauma than an ear with small pneumatisation (small volume), because pressure variation is equilibrated better in the ear with a smaller volume.

Transmucosal gas exchange through mastoid air cells–mastoid mucosa–blood is a slow, passive process, but it also serves as a constantly acting pressure regulation system for the middle ear, even when the Eustachian tube is not working, as in sleep. However, this gas exchange pathway cannot adequately handle a sudden change in atmospheric pressure in aviation.[20] Thus, under normal physiological conditions, gas exchange across the Eustachian tube is the only direct communication between the middle ear and ambient environment, and the only exchange pathway capable of equilibrating the variation between ambient pressure and middle-ear pressure.[21]

In a study by Sade *et al.*[12] on the incidence of air travel barotrauma in 'chronic ear' patients (patients with secretory otitis media, atelectasis or previously operated cholesteatoma), mastoid pneumatisation was found to be significantly higher in ears with barotrauma in normal controls, with none of the chronic ears having barotrauma. In a similar way, in the current study, mean temporal bone pneumatisation volume was high in ears with barotrauma, measuring at 91.05 cm^3. However, in Sade and colleagues' study, the mean temporal bone pneumatisation volume in ears with barotrauma was 16.8 cm^2. This difference reflects the different methods used to assess pneumatisation: while we used CT to examine the temporal bone, Sade and colleagues used X-rays to assess only the mastoid. In addition, in the study by Sade *et al.*, no otolaryngology examination was conducted before the flight, and there were possible differences in the cruising altitudes between patients.

In the present study, all aircrew members with temporal bone pneumatisation that ranged from 11.3 cm^3 to 70.4 cm^3 had no barotrauma. It seems that a well-functioning Eustachian tube can equalise pressure change in temporal bone pneumatisation volumes ranging from 11.3 cm^3 to 70.4 cm^3. In contrast, barotrauma was detected in aircrew members with temporal bone pneumatisation of 11.2 cm^3 or lower, which may be a result of the association of this particular pneumatisation level with Eustachian tube dysfunction, as reported in the literature.[22,23] Thus, in the present study, patients with temporal bone pneumatisation of 11.2 cm^3 or lower may have unidentified Eustachian tube dysfunction despite having passed the nine-step screening test.

No significant correlation was detected between temporal bone pneumatisation of 11.2 cm^3 or lower and barotrauma grade. Hence, while this level of pneumatisation is related to the presence of Eustachian tube dysfunction, the results obtained for ears with temporal bone pneumatisation of 11.2 cm^3 or lower must be viewed cautiously, especially given the small number of ears ($n = 12$) in this group.

We detected symmetry of mastoid pneumatisation in 96 per cent (76 out of 79) of all aircrew members. Pneumatisation symmetry has previously been reported to occur in 72–99 per cent of the general population.[24,25]

In the current study, barotrauma was detected in 28.4 per cent of all ears. This means that barotrauma can be avoided in approximately 3 out of 10 aircrew members if temporal bone pneumatisation is added to the strict criteria of middle-ear pressure and Eustachian tube function in the pre-hire medical assessment of aircrew members.

- The relationship between temporal bone pneumatisation and middle-ear barotrauma has been debated previously
- The volume of mastoid air cells and its communicating air cells must be measured with computed tomography when correlating with barotrauma risk
- Pneumatisation volume of the mastoid and its communicating air cells of 11.3–70.4 cm^3 was a reliable predictor of barotrauma avoidance when flying
- A direct relationship existed between temporal bone pneumatisation and barotrauma grade in ears with pneumatisation of 71 cm^3 or greater
- There was no significant correlation between temporal bone pneumatisation of 11.2 cm^3 or lower and barotrauma grade

Based on the findings of the current study, and the 2014 study conducted by the first author,[4] we hypothesise that temporal bone pneumatisation ranging from 11.3 cm^3 to 70.4 cm^3, together with a resting middle-ear pressure within −55 and + 50 mmH_2O and good nine-step inflation–deflation test results, can be considered reliable predictors of barotrauma avoidance in aircrew members.

The current study is preliminary, and further studies, conducted on larger numbers of aircrew members, are needed to assess the effect of temporal bone pneumatisation on the development of barotrauma in this group of individuals.

Conclusion

Pneumatisation volume of the mastoid and its communicating air cells ranging from 11.3 cm^3 to 70.4 cm^3 serves as a reliable predictor of the avoidance of middle-ear barotrauma associated with flying in aircrew members who have a normal resting middle-ear pressure and good Eustachian tube function. As established in this study, the higher the pneumatisation

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volume of the mastoid and its communicating air cells is above 71 cm^3, the greater the degree of middle-ear barotrauma experienced by aircrew members.

Competing interests. None declared

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