Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

Executive summary

Impact of cabin pressure on the well-being of aircraft passengers

A case study

Problem area
Changing passenger demographics, the advent of ultra-long-haul services and specific health issues such as hypoxia and deep vein thrombosis have increased concerns about the impact of the aircraft cabin environment on the health and well-being of passengers. Particular aspects are the impact of the cabin pressure level, which in cruise may reach to a level corresponding to normal atmospheric pressure at the height of 8000 ft. A better understanding is needed of physiological and psychological indicators of passenger health and well-being in a realistic aircraft cabin environment (including realistic cabin pressure levels).

Description of work
In the EC-funded project Ideal Cabin Environment (ICE) extensive experiments have been conducted in realistic simulated aircraft cabin environments in Watford, UK and Holzkirchen, Germany. The Flight Test Facility (FTF) in Holzkirchen concerns the first 16 meters of a complete wide-body aircraft within a pressure vessel, which allows to simulate realistic cabin pressure levels. In the FTF 29 flights of 7

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hours with approximately 40 passengers in each flight were simulated. The experimental conditions for cabin pressure, temperature, humidity, and noise in these flights were designed with a D-optimal design applied to complement pre-selected conditions. Subjects were carefully selected to represent realistic passenger demographics and, in addition, to investigate specific risk groups. Various physical, physiological, and psychological measurements were taken during flight, both continuously and at five specific instances (baseline, 3 cruise exposures, and post-baseline). The experiments have resulted in an extensive data set. To obtain first conclusions, the finger pulse oximetry results have been analysed in the 4 tests involving risk subjects with cardiopulmonary health conditions.

Results and conclusions
The 4 specific tests have been performed at ground level (2231 ft at the site of FTF) and at 8000 ft, two test for each cabin pressure level. During the tests at ground level only a slight decrease of the saturated oxygen in the peripheral blood flow (SpO2) has been observed. During the tests reaching 8000ft there is a clear drop of SpO2 level, which is a normal physiological response. Age-dependency of the SpO2 values has also been analysed. Finally, the probabilities of occurence of SpO2-level below 85% - the widely accepted threshold for a recommendation of supplemental in-flight oxygen – have been analysed.
It is concluded that for passengers on average this probability of occurrence is below 0.001, whereas elderly people or passengers with a cardiovascular disease (New York Heart Association class 2 heart failure) or a pulmonary disease (Chronic Obstructive Pulmonary Disease patients with Medical Research Council Dyspnoea grade 2) have a generally low risk of experiencing a critically low level of saturated oxygen in peripheral blood flow. This result is relevant since the group of elderly people is growing and travels more than in the past.

Applicability
This study contains the conclusions from the first analyses on the extensive ICE data set. Further analysis and discussion might yield more substantial recommendations for passengers with pre-existing cardiopulmonary problems. The extensive data set from the experiments can be analysed for other impact on health and well-being, leading to additional technical and behavioural recommendations. The extensive data set may also be used to model the impact of cabin environment, passenger characteristics and flight characteristics on health and well-being of passengers. Such models may be used to optimise the cabin environment and the passenger behaviour.

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A case study

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Contents

IMPACT OF CABIN PRESSURE ON ASPECTS OF THE WELL-BEING OF AIRCRAFT PASSENGERS – A LABORATORY STUDY

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Abstract

In the European Project Ideal Cabin Environment a study on the impact of different levels of the environmental parameters, such as pressure, on the well-being of aircraft passengers was performed in a simulated aircraft environment. Each test with 40 different subjects, including those with relevant health concerns consisted of a pre-baseline, a simulated 7h flight and a post-baseline. The test design is described in detail as well as the achieved levels of environmental conditions. An analysis of oxygen saturation in peripheral blood flow (SpO_2) has been performed on measurements by finger pulse oximetry. Subjects with cardiovascular or pulmonary health concerns did show significantly lower levels of SpO_2 compared to healthy subjects. The probability of achieving a SpO_2 level below a critical level of 85% was smaller 0.001 for all groups except for those subjects with cardiopulmonary problems older than 60 years.

1 Introduction

The EC-funded project Ideal Cabin Environment (ICE) addresses concerns about the unknown combined effects of cabin environmental parameters, such as cabin pressure, relative humidity, temperature, and noise, on the health and well-being of passengers in commercial aircraft. Changing passenger demographics, the advent of ultra-long-haul services, and specific health issues such as hypoxia or deep vein thrombosis, have all combined to increase concerns. ICE is now almost through its three-year project period and during this time a campaign of tests on about 1500 passengers representing a broad spectrum of the traveling public has been completed – including groups with relevant health concerns (respiratory and cardiovascular).

2 Description of Tests

The impacts of varying levels of the above mentioned environmental parameters on subjects were investigated using unique large-scale aircraft cabin environment facilities to determine optimum individual and combined levels for human well-being. While a study focusing on ventilation rates was performed in the Aircraft Cabin Environment (ACE) rig at the Building Research Establishment Ltd. (BRE) in Watford, UK [1] the study reported in this paper was conducted at the Flight Test Facility (FTF) at the Fraunhofer Institute for Building Physics (IBP) in Holzkirchen, Germany.

2.1 The Flight Test Facility

The FTF consists of a 30 m long pressure vessel which holds the first 16 m of a complete wide-body aircraft (see Figure 1).

Figure 1: Front segment of an A310-200 inside the pressure vessel.

The interior of the aircraft was maintained to give subjects a realistic impression of flying (see Figure 2) while the main environmental parameters can be varied and controlled: air pressure, air and fuselage temperature, relative humidity, noise and vibration, lighting, ventilation rate, etc. [1]

Figure 2: Interior of the FTF aircraft cabin.

2.2 Test Design

To investigate the impact of aircraft cabin environment on the passengers' well-being a subject study has been performed varying cabin pressure, relative humidity, air temperature and noise level while other environmental parameters were kept constant.

The study consisted of 29 simulated 7h flights lasting from November 2006 to January 2007. For four of these flights subjects with slight pulmonary or cardiovascular diseases were acquired to examine the effects on passengers at-risk. To take the differences between exposition and the general state into account baselines of 30min before and after each simulated flight were introduced. Thus each test consisted of 30min pre-baseline, 30min take-off, 30min stabilization of environmental conditions, 5.5h cruise, 30min landing, and 30-min post-baseline, so that each test had a total length of 8h.

During all baselines the physical parameters were controlled to the same level, while the levels during the simulated flights differed as reported in Table 4 to Table 6. The levels were chosen according to sensible values for an aircraft cabin environment: ambient, 875 hPa, 810 hPa, and 753 hPa for barometric pressure; 10% (very low but usual in aircraft cabins), 25% (rather low, but possibly achievable within aircraft cabins), and 40% (medium but very high for aircraft cabins) for relative humidity; 21°C, 23°C, and 25°C for temperature (all near the expected thermal comfort region); 55.1 dB(A) (background noise with just HVAC systems running), 64 dB(A) (quite high, but hardly achievable for aircraft and still a sensible aircraft sound), 69 dB(A), and 74 dB(A) (usual for aircraft) as noise levels.

After reserving two tests to investigate the impact of pressure profiles and four tests with subjects at-risk a D-optimized design was generated by the National Aerospace Laboratory (NLR) based on a full-factorial set of candidate points from the parameters pressure, humidity and temperature at a fixed noise level of 74 dB(A). The impact of noise was studied in five separate tests, with corresponding levels to those of the tests with subjects at-risk. Figure 3 depicts the resulting test design.

Two Questionnaires with approximately 100 items each have been developed and supervised under responsibility of the Unit of Human Factors and Ergonomics, Medical University of Vienna. They were presented via PDAs which have been explained to the subjects during the distribution of the first questionnaire.

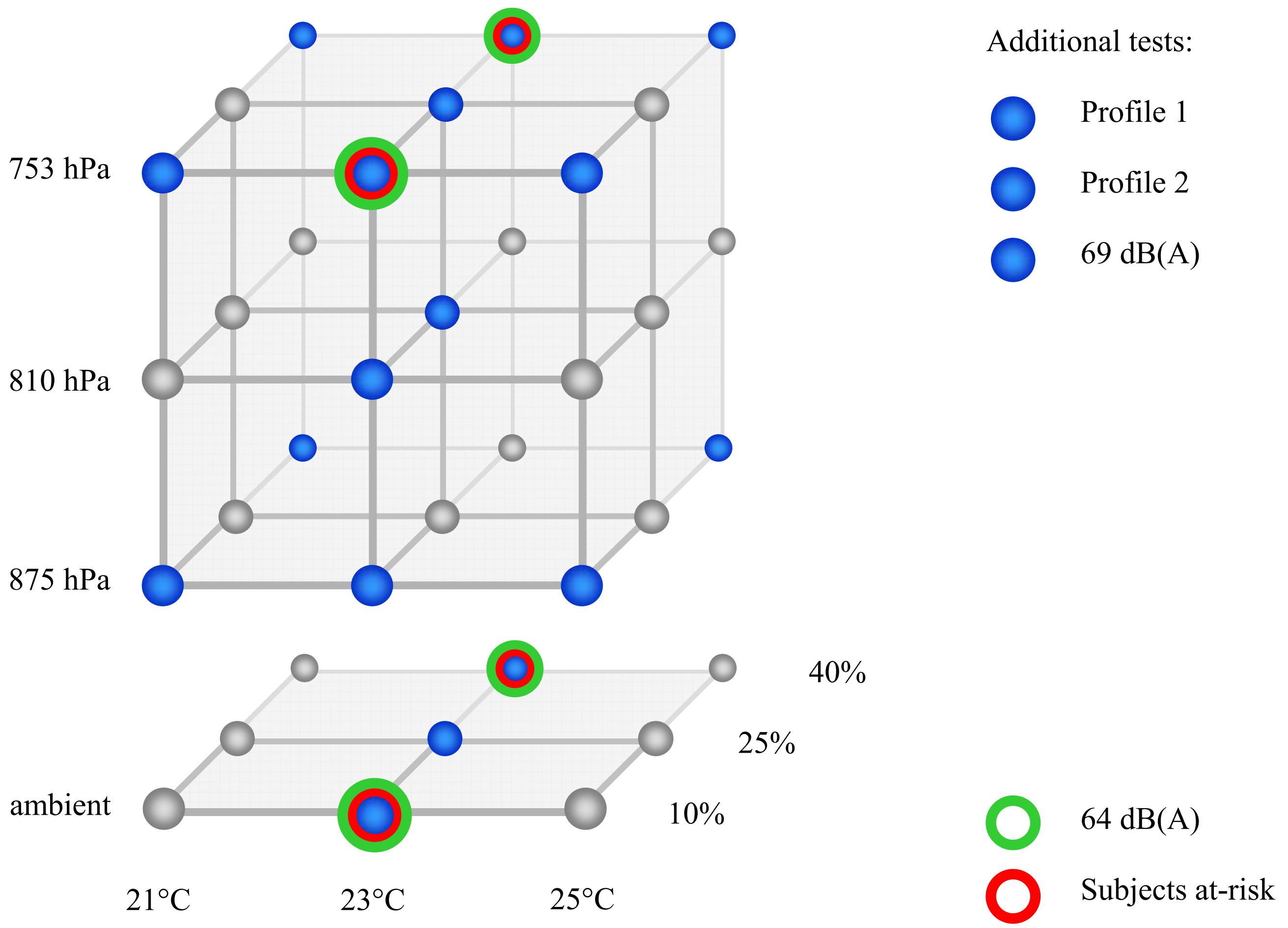

Figure 3: Visualization of the test design. Blue bullets depict the selected tests for the study at FTF.

The items of the first questionnaire considered the subjects' state of comfort, mood, symptoms and behavior. It was distributed five times during each test: in the baselines and at 90 min, 240 min and 390 min after start of each test. The second questionnaire asked for the subjects' personal characteristics, their health status, general well-being and sensitivity to certain environmental situations. This questionnaire was handed out right after the questionnaire at 240 min after start of each test.

The subjects were allowed to move inside the cabin and to spend their time on their own way apart from the filling out of questionnaires. Meals and drinks were provided on a regular basis, lavatories were onboard.

2.3 Subject Selection

For each test in the FTF test rig 40 healthy subjects were selected. The flying public was addressed by accounting for three different age groups and gender according to the subject profile in Table 1.

Table 1: Target subject profile with respect to gender and age.

age	18 – 34	35 – 49	50+
male	6 or 7	7 or 6	7
female	7 or 6	6 or 7	7

For four tests a sub-sample of 20 persons with diseases of particular interest was selected to achieve equal numbers of persons with a cardiovascular disease (New York Heart Association (NYHA) class 2 heart failure) or a pulmonary disease (chronic obstructive pulmonary disease (COPD) patients with Medical Research Council (MRC) Dyspnoea grade 2). The remainder of 20 subjects represented the healthy public (referred to as having a normal health status). These tests received approval of both, the research ethics committee of the Royal Free Hospital & Medical School in London, UK and ethics committee of the Ärztekammer Nordrhein in Düsseldorf, Germany. All subjects gave their written consent before participating in this research.

2.3. 1 Subject Inclusion Criteria

1) Healthy adults.
2) Adults with NYHA Grade 2 heart failure.
3) Adults with MRC Dyspnoea Grade 2
4) Persons who are able to take care of their basic personal needs such as toileting.
5) Those who are able to communicate their needs.
6) Willing to participate in the study and sign an informed consent.

2.3.2 Subject Exclusion Criteria

1) Age less than 18.
2) Persons with NYHA Grade 3 heart failure or higher.
3) COPD patients with MRC Dyspnoea Grade 3 or higher.
4) Recent myocardial infarction within the last month.
5) Persons with established DVT.
6) Persons known to have a procoagulant state.
7) Persons with uncontrolled epilepsy.
8) Problem with mobilizing.
9) History of intravenous drug use.
10) Inability to consent for the study.

2.3.3 Additional Subject Exclusion Criteria for the pressurized FTF test rig

1) Damage of the tympanic membrane.
2) Diving accident or surgery in the last six months.
3) Anaemia.
4) Diabetes mellitus under medication.
5) Pregnancy.

2.3.4 Selected Profile

The achieved subject profiles considering the target age and gender profile and the selection criteria are reported in Table 2 and Table 3.

Table 2: Number of subjects in the four tests with sub-samples of subjects with pulmonary or cardiovascular disease.

health status	normal	cardiovascular	pulmonary
males	38	32	17
females	42	6	21
total	80	38	38

Table 3: Age characteristics of each age class and number of subjects of both genders for subjects with normal health status, at risk and overall.

health status	age			n	
	Class	mean	stdv.	males	females
normal	18 - 34	25.6	4.5	163	181
	35 - 49	42.1	4.0	145	134
	50+	61.1	7.3	190	183
	total	43.5	16.1	498	498
risk	18 - 34	29.6	6.1	2	4
	35 - 49	42.2	4.6	12	18
	50+	63.0	7.2	73	47
	total	57.7	12.0	87	69
total	18 - 34	25.9	4.5	165	185
	35 - 49	42.1	4.0	157	152
	50+	61.3	7.3	263	230
	total	45.5	16.3	585	567

3 Environmental Conditions

3.1 Physical Environment

The physical variables have been measured in one minute intervals throughout each test. The barometric pressure has been monitored at one location inside the cabin. The levels measured are reported in Table 4, only those tests have been considered where the standard deviation of the measurements was below 25.0 hPa. Similarly Table 5 depicts the measured levels of relative humidity with only those tests included where the standard deviation was below 4 % and the mean did not differ more than 4 % from the target value. It was measured using capacitive sensors in each row inside the cabin at 1.1 height. Air temperature has been averaged over measurements with dry bulb thermometers in 0.1 m, 0.6 m and 1.1 m height at every second seat. Their values are reported in Table 6 with only those tests considered where the standard deviation was below 1.5°C and the mean did not differ more than 1.5°C from the target value.

Table 4: Measured levels of the barometric pressure during the five questionnaire intervals and throughout the whole cruise phase.

Phase	Level 1 [hPa]		Level 2 [hPa]		Level 3 [hPa]		Level 4 [hPa]	
	mean	stdv.	mean	stdv.	mean	stdv.	mean	stdv.
Pre-Baseline	937.4	0.3						
Post-Baseline	938.4	0.2						
Cruise 1	937.8	0.2	873.7	0.2	812.1	0.2	752.2	0.2
Cruise 2	939.1	0.2	875.6	0.2	814.1	0.1	753.9	0.2
Cruise 3	940.8	0.1	875.8	0.2	814.5	0.2	754.6	2.5
Cruise total	938.9	0.9	875.2	0.8	813.9	0.8	753.7	1.2

Table 5: Measured levels of the relative humidity during the five questionnaire intervals and throughout the whole cruise phase.

Phase	Level 1 [%]		Level 2 [%]		Level 3 [%]	
	mean	stdv.	mean	stdv.	mean	stdv.
Pre-Baseline			23.93	0.78		
Post-Baseline			25.18	1.73		
Cruise 1	11.95	0.99	23.69	0.70	40.97	1.51
Cruise 2	10.18	0.88	23.98	0.72	40.93	1.29
Cruise 3	10.24	0.90	23.47	0.78	41.13	1.52
Cruise total	10.93	1.54	24.10	1.20	40.93	1.60

Table 6: Measured levels of the ambient temperature during the five questionnaire intervals and throughout the whole cruise phase.

Phase	Level 1 [°C]		Level 2 [°C]		Level 3 [°C]	
	mean	stdv.	mean	stdv.	mean	stdv.
Pre-Baseline			23.11	0.40		
Post-Baseline			22.44	0.58		
Cruise 1	21.30	0.83	22.81	0.54	24.84	0.47
Cruise 2	20.72	0.66	22.66	0.55	24.24	0.50
Cruise 3	20.41	0.66	22.53	0.56	24.39	0.54
Cruise total	20.78	0.92	22.49	0.75	24.29	0.58

The background noise consisted of in-flight recordings of an A320-flight including take-off and landing. These sounds are reproduced by diverse loudspeakers distributed along the cabin in the ceiling and dado panels. Its levels have been calibrated inside the empty cabin with HAVC systems running before performing the study with microphones positioned 0.65 m above each seat and ca. 0.15 m in front of the backrest. The levels reached are reported in Table 7.

Table 7: Background noise levels.

Target Level [dB(A)]	Background Noise [dB(A)]	
	mean	stdv.
74	73.8	1.1
69	68.8	1.1
64	63.8	1.1
HVAC systems	55.1	2.5

Vibrations are induced via the same playback system as background noises. They are generated by shakers mounted underneath each seat. In this study the vibrations were changed linearly with the background noise and calibrated at the transition point of the seat frame and seat rail. Table 8 depicts the weighted total accelerations.

Table 8: Background vibration levels.

Target Level [dB(A)]	Background Noise [dB(A)]	
	mean	Stdv.
84	83.8	4.2
79	78.8	4.2
74	73.8	4.2
HVAC systems	77.2	1.2

3.2 Air Quality measurements

Besides diverse VOCs the following compounds have been measured by EADS Innovation Works in 1 min intervals throughout each test: CO_2 with FT-IR with 5 m gas cell, Ozone with UV Photometry, and TVOC with an online FID. Table 9 reports the means of these measurements and their standard deviation.

Furthermore particulates (PM_{10} and PM_2) have been measured by IBP throughout each test in 1.1 m height at two locations inside the cabin with Grimm Portable Dust Monitors. Their mean levels are reported in Table 10 as well as the levels of airborne bacteria and fungi investigated by IBP's microbiologists. These have been monitored with an Aerosol Sampler AirPort MD8 with gelatin membrane filters at certain point in a height of 0.8 m at two locations inside the cabin. Subsequently cultivation methods have been used to analyze the amount of colony forming units (CFU).

Table 9: Measured levels of CO_2, Ozone and TVOC during the five questionnaire intervals and throughout the whole cruise phase.

Phase	CO_2 [ppm]		Ozone [ppb]		TVOC [ppm]	
	mean	stdv.	mean	stdv.	mean	stdv.
Pre-Baseline	853.30	9.61	1.99	0.52	1.08	0.03
Post-Baseline	845.56	28.26	1.17	0.40	1.04	0.11
Cruise 1	810.87	9.25	2.56	0.50	1.09	0.10
Cruise 2	833.32	10.49	2.41	0.71	1.02	0.02
Cruise 3	826.81	9.40	1.36	0.41	1.01	0.06
Cruise total	837.72	27.94	2.24	1.21	1.07	0.10

Table 10: Measured levels of particulate matter (PM_{10} and PM_2), bacteria and fungi during the five questionnaire intervals and throughout the whole cruise phase.

Phase	PM_{10} [µg/m³]		PM_2 [µg/m³]		Bacteria [CFU/m³]		Fungi [CFU/m³]	
	mean	stdv.	mean	stdv.	mean	n	mean	n
Pre-Baseline	1.33	2.42	4.45	3.03	4.32	27	1.36	27
Post-Baseline	1.54	2.50	4.81	3.18	4.29	28	1.67	28
Cruise 1	1.17	2.09	4.40	2.62	n.a.		n.a.	
Cruise 2	0.88	2.13	3.51	2.75	<1	1	6.67	1
Cruise 3	1.31	3.89	4.10	4.46	15.76	11	1.21	11
Cruise total	1.33	2.56	4.03	3.38	n.a.		n.a.	

4 Physiological Measurements

Before and after each of the tests with subjects with slight pulmonary and cardiovascular diseases a mini-lung function test with Clement Clarke spirometers was performed and blood samples were taken by investigators of the University College London. The latter ones were drawn into Vacutainer blood collecting systems prepared with Sodium Citrate and EDTA.

A notebook-based modified Békésy method was used by researchers from University of Oldenburg to perform an audiogram with a subset of six subjects before and after 15 tests without subjects at-risk.

During the questionnaire phases of each test investigators of the Medical University Vienna took the subjects' blood pressure with Tensoval ambulatory blood pressure units by Hartmann. Additionally each subject wore an electrocardiogram recorder by Medilog TOM GmbH throughout the test logging signals for the analysis of heart rate, heart rate variability, respiratory frequency and electrodermal activity.

To measure the motor activity investigators of the German Aerospace Center equipped each of the subjects with miniature apparatuses "BMD-Actometer" (company Gefatec GmbH, Tiefenbach, Germany) at their left thigh. Furthermore each subject wore a finger pulse oximeter (Nonin's WristOx® 3100) throughout the whole test.

5 Analysis of Finger Pulse Oximetry

While the air pressure inside aircraft cabins can be as low as 753 hPa during normal operation (which equals an equivalent height of 8000 ft) the saturation of oxygen in the arterial blood flow decreases. Gong [4] gives a short overview of the physiologic responses, pointing out that passengers with cardiopulmonary problems may not be able to compensate this decrease in pressure for several reasons. Since then several studies have been performed either in pressure chambers or at ground with simulating the height by giving breathing air containing 15% oxygen only. Most of these studies concentrated on patients with pulmonary diseases, like [5] where patients with COPD, interstitial lung disease and cystic fibrosis were studied. In this investigation PaO_2 levels decreased to 6.9 kPa when providing 15% oxygen, while 8.37 kPa were measured at sea level. Only few investigations are published reporting measurements of SpO_2 in-flight. Most recently Akerø et al. [6] studied COPD patients traveling by aircraft to a recreation center. They report a decrease from 96% SpO_2 at sea level to 90% SpO_2 at 6000 ft cabin altitude.

The software package Statistica® (Statsoft, Tulsa, OK, USA) has been used for statistical analysis of the measurement results of the finger pulse oximetry. Statistical tests were considered significant, when two-tailed p-values were smaller than 0.05.

Only those tests with subjects with cardiopulmonary health conditions participating have been analyzed. In all of these flights subjects with a cardiovascular disease (NYHA class 2 heart failure) or a pulmonary disease (COPD patients with MRC Dyspnoea grade 2) participated as well as a control group of approximately the same size. These four tests have been performed at two different equivalent heights, with two tests at each height: ground level (equals 2231 ft at the site of the Flight Test Facility) and 8000 ft.

The measurements of the saturated oxygen in the peripheral blood flow (SpO_2) taken by finger pulse oximetry have been averaged for the 20 min intervals of those stages within the tests when questionnaires were distributed. These values are depicted in Figure 4 for the whole sample. During tests reaching 8000 ft there is a clear drop of SpO_2 levels: starting from 96.0% during the pre-baseline the level reaches ca. 91.0%, whereas the values at 0.5 h after reaching cruise level is significantly higher than the subsequent ones. During tests at ground level only a slight decrease of SpO_2 levels can be observed (from 95.8% to 95.0%). A higher activity level before start of the test or some effects due to fatigue might be possible explanations.

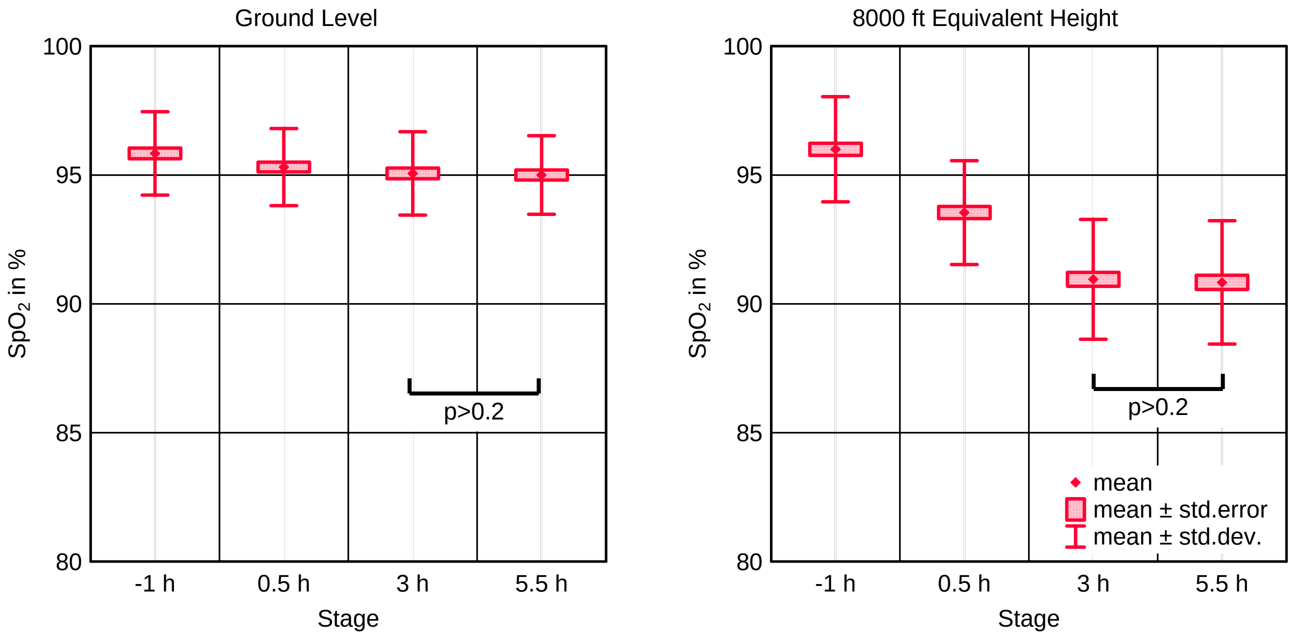

Figure 4: Measurements of SpO2 taken by finger pulse oximetry have during the investigation stages: pre-baseline 1 h before reaching cruise level at ground level and 0.5 h, 5.5 after reaching cruise level. Only the probabilities of those differences are reported, which are NOT significant using a t-test.

A t-test for paired samples showed no significant differences between SpO_2 levels after 4, 6.5 and 7.5 hours at ground level and at 4 and 6.5 hours at 8000 ft equivalent height. Thus the data of the stages at 4 and 6.5 hours have been pooled for the following analyses.

First the SpO_2 levels of the three groups differing in health status (normal, cardiovascular and pulmonary) have been compared at both equivalent heights using a t-test for independent samples. At ground level there is a significant difference between subjects with normal health status and those with a cardiovascular disease only. However, both groups of subjects at risk differ significantly from those with normal health status at an equivalent height of 8000 ft (see Figure 5).

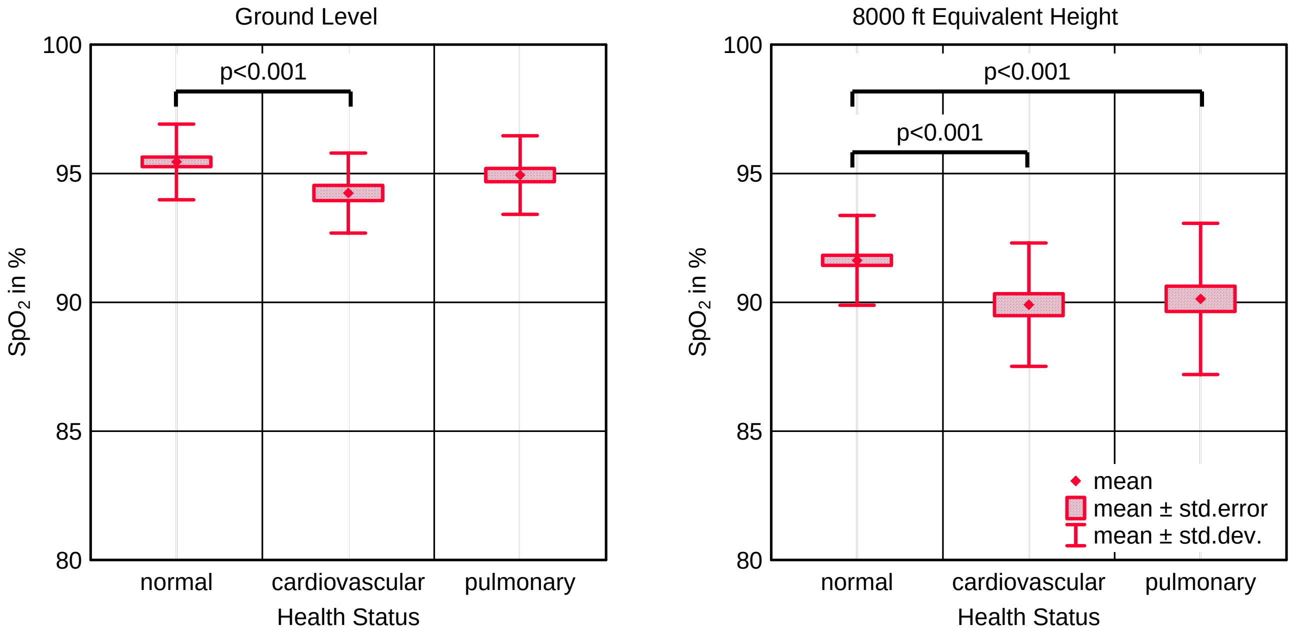

Figure 5: SpO_2 levels pooled from stages after 4 and 6.5 hours at both equivalent heights for each group differing in health status. Only the probabilities of those differences are reported which are significant using a t-test.

Since SpO_2 levels decrease generally with increasing age the sample has been divided into two age groups for the subsequent analysis: a younger group below 60 years and a group consisting of elderly subjects with an age equal or above 60 years. Again a t-test for independent samples has been used to test whether the SpO_2 levels for each health status at each equivalent height differ significantly between both age groups. While there is a significant difference for healthy subjects at ground level, there is none for both groups of subjects at risk (see Figure 6). At an equivalent height of 8000 ft the SpO_2 level of all sub-samples of different health status differs significantly between both age groups.

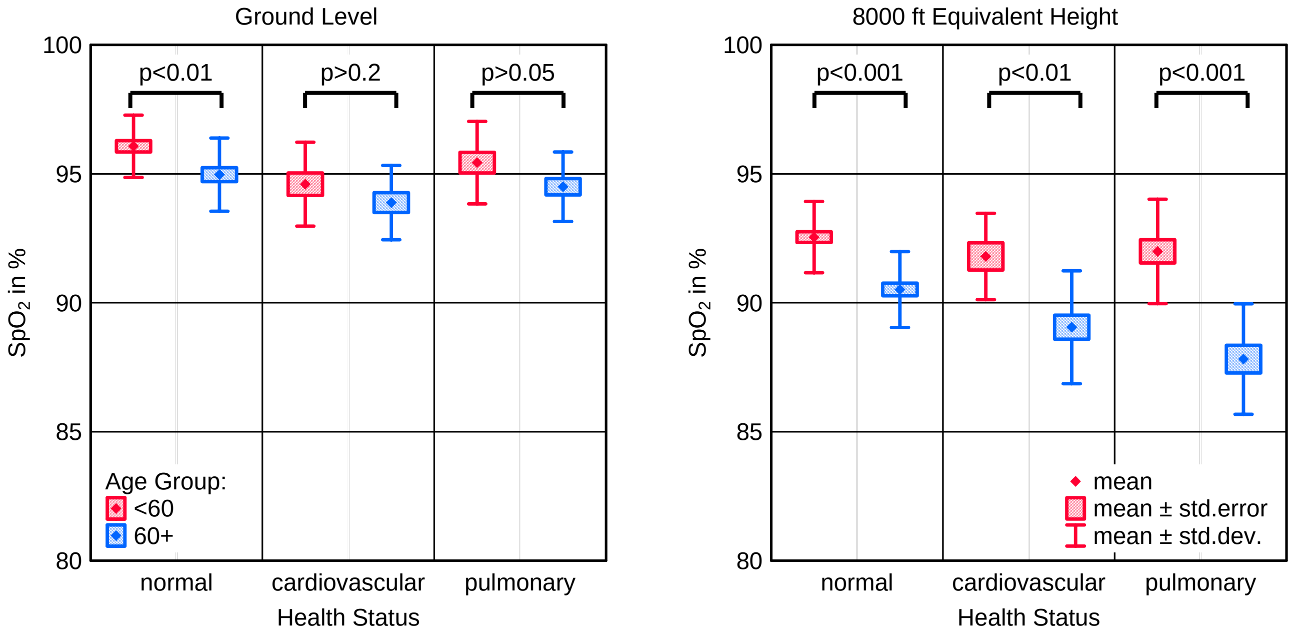

Figure 6: SpO_2 levels pooled from stages after 4 and 6.5 hours at both equivalent heights for each sub-sample differing in health status and age group.

For each of the twelve sub-samples a Kolmogorov-Smirnov test showed no significant differences between the distribution of the SpO_2 levels and a normal distribution ($p>0.20$ for each of the twelve sub-samples). Thus assuming an underlying normal distribution the probabilities of the occurrence of a SpO_2 level below a critical value of 85% have been calculated (see Table 11). This level is widely accepted as a threshold for a recommendation of supplemental in-flight oxygen [4].

Table 11: probabilities of the occurrence of a SpO_2 level below 85% for each of the groups. Note that n refers to the number of pooled mean values from the two stages after 4h and 6.5h.

Level	Age	Health Status	n	$p_{SpO2<85\%}$
ground	<60	normal	30	<0.001
ground	<60	cardiovascular	14	<0.001
ground	<60	pulmonary	16	<0.001
ground	60+	normal	26	<0.001
ground	60+	cardiovascular	14	<0.001
ground	60+	pulmonary	18	<0.001
8000 ft	<60	normal	44	<0.001
8000 ft	<60	cardiovascular	10	<0.001
8000 ft	<60	pulmonary	20	<0.001
8000 ft	60+	normal	36	<0.001
8000 ft	60+	cardiovascular	22	0.032
8000 ft	60+	pulmonary	16	0.094

6 Result and conclusions

From these probabilities it can be concluded, that elderly people or passengers flying with a cardiovascular disease (NYHA class 2 heart failure) or a pulmonary disease (COPD patients with MRC Dyspnoea grade 2) have a generally low risk of experiencing a critically low level of saturated oxygen in peripheral blood flow, but their risk is still higher than that of healthy or/and younger passengers. Thus these measurements of oxygen saturation in peripheral blood flow are worthy of further debate from the authors' viewpoint. Further analysis and discussion of these results might yield more substantial recommendations for passengers with preexisting cardiopulmonary problems than they are currently available.

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