Effect of increased cabin recirculation airflow fraction on relative humidity, CO_2 and TVOC

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Abstract. In the CleanSky 2 ComAir study, subject tests were conducted in the Fraunhofer Flight Test Facility cabin mock-up. This mock-up consists of the front section of a former in-service A310 hosting up to 80 passengers. In 12 sessions the outdoor/recirculation airflow ratio was altered from today's typically applied fractions to up to 88% recirculation fraction. This leads to increased relative humidity, carbon dioxide (CO_2) and Total Volatile Organic Compounds (TVOC) levels in the cabin air, as the emissions by passengers become less diluted by outdoor, dry air. This paper describes the measured increase of relative humidity, CO_2 and TVOC level in the cabin air for the different test conditions.

1. Introduction

The ComAir study investigates the applicability of a passenger-count based ventilation in the aircraft cabin. In most commercial aircrafts, the outdoor air to ventilate the cabin is extracted from the engine compressor stages upstream the combustion chamber. In the mixing chamber, this outdoor air is mixed with HEPA filtered recirculation air coming from the cabin. From there, the supply air travels through the riser ducts to the cabin air outlets, from where it enters the cabin [Oehler 2005].

The moisture in the cabin is typically low, because the outside air is cold and thus dry. The major source for humidification are the passengers themselves, emitting water by breathing and sweating. Along with this, passengers exhale CO_2 and emit VOCs (volatile organic compounds) as a product of metabolism; VOCs are also emitted from toiletry and cleaning agents. These are diluted by the outdoor air, while the recirculation airflow does not alter the composition. Typical target values that the environmental control system (ECS), the system that provides air supply, thermal control and cabin pressurization for the crew and passengers, shall comply with are summarized in [ASHRAE 161, 2007]:

- Minimum cabin air pressure limited to 750 hPa (equivalent to pressure altitude of 8.000 ft. or 2.400 m above sea level)
- Temperature range in the cabin between 18.3 and 23.9 °C (65 to 75 °F)

- Minimum outside airflow rate per passenger of 3.5 l/s (7.5 cfm)
- Recommendation of 9.4 l/s (20 cfm) total flow, to be met by outside and filtered recirculated air

In the building sector, the demand controlled ventilation already today implements a philosophy based on reducing the supply airflow rate to the actually required amount thereby avoiding excessive ventilation and thus energy use. Often, CO_2 concentration in the occupied space is used as a feedback signal for the control of the ventilation system as it is closely correlated with other human emissions and the occupation density [UBA 2008]. [DIN EN 15251, 2012] gives quality criteria for the indoor air based on CO_2 level stating that concentrations below 800 ppm are optimal and concentrations above 1.200 ppm are not acceptable. Whether these design values can be directly applied to aircraft is not clear because buildings typically do not have a high-efficiency particulate air (HEPA) filtration on recirculation air, whereas this is standard for aircrafts. A comparison of building and aircraft ventilation requirements is provided in [Zavaglio et al., 2018].

[Giacona et al. 2013] performed a series of CO_2 measurements in commercial flights and found that average CO_2 concentrations varied between 925 and 1449 ppm. Unfortunately, the publication is not clear on whether the CO_2 readings were compensated for pressure or not. Typically, a pressure correction needs to include the factor $1.013/p_{cabin}$. [Vaisala 2019]. In a similar approach on 179 domestic US flights [Cao et al. 2019] found an average CO_2 concentration of 1353±290 ppm in the cabin. The researchers clearly state that sensor readings were pressure compensated.

In this context, the ComAir study was proposed to further investigate aircraft ventilation strategies and indoor air quality impact on passengers.

The ComAir study was approved by the Ethics committee of the Faculty of Medicine, Ludwig-Maximilians-University, Munich (ID: 19-256) and written informed consent was obtained from all participants. The tests were performed in November 2019 and thus before the Sars-Cov-2 pandemic was an issue in Germany. This paper summarizes the resulting CO_2, humidity and TVOC levels measured in a cabin mock-up for the different outdoor air intakes.

2. Method

To investigate the effect of reduced outdoor air intake and increased recirculation airflow rate, a randomized controlled study with a total of 559 different participants was conducted. The study was hosted in the Flight Test Facility (FTF, https://www.hoki.ibp.fraunhofer.de/vr/virtual-tour_IBP/) located at the Fraunhofer-Institute for Building Physics in Holzkirchen, Germany.

2.1. Flight Test Facility Test Setup

In the FTF, a former in-service front section of an A310 has been placed into a low pressure vessel (Figure 1a). The cabin (Figure 1b) hosts up to 80 passengers and is surrounded by crown, forward galley, cockpit, avionics, triangles, cargo and bilge compartments. The aircraft mock-up consists of the section from nose to front wing box wall. A measurement system to assess temperature, humidity, CO_2 and VOCs was integrated (Figure 1c). The ECS is emulated by a building type air conditioning system with a sub freezer that cools and dehumidifies the supply air to a dew point of -20 °C. Thus, a similar low humidity level of supply air can be reached as in flight. Air is supplied through ceiling outlets above the stowage bin and lateral outlets that have been added to better emulate today's cabin design. The recirculation air is extracted from the cabin and HEPA filters provided by aircraft supplier. A schematic view of the airflow path is shown in Figure 1d.

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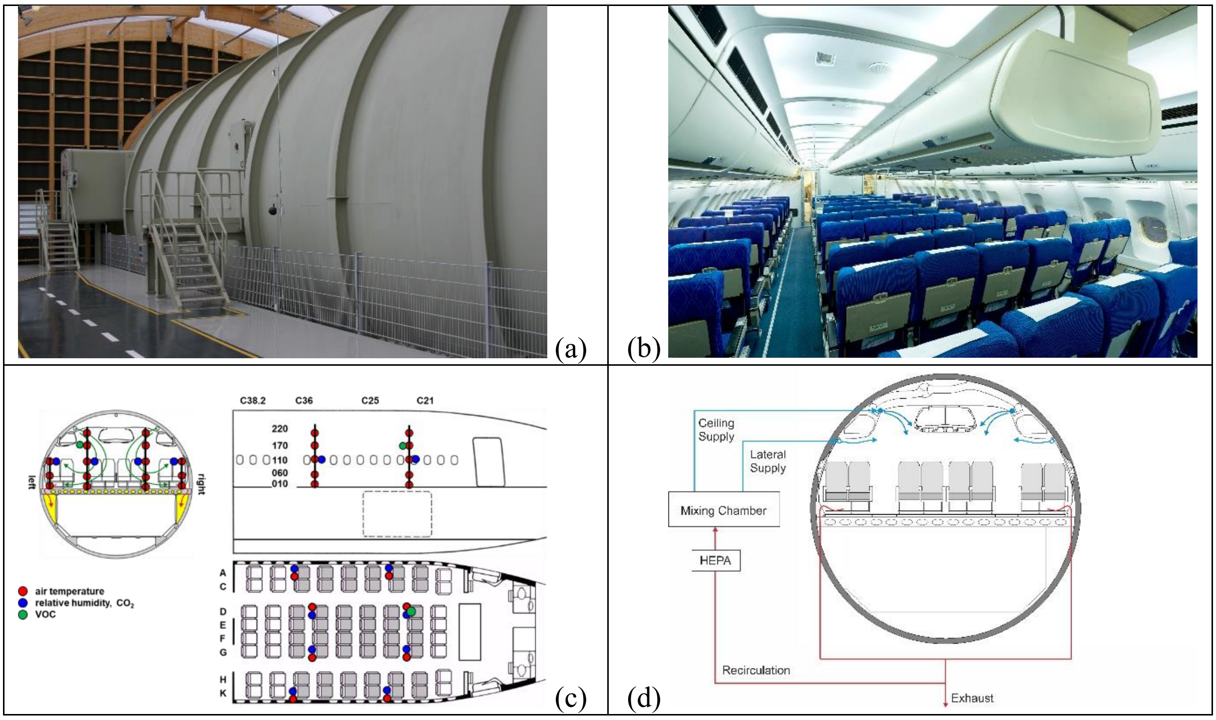

Figure 1: (a) Low pressure vessel of FTF, (b) Aircraft cabin mock-up, (c) Aircraft mock-up in the low pressure vessel, (d) schematic ventilation pattern

The following sensor types and specifications were used:

- Temperature: Four-wire PT100 thermocouples with an accuracy ±0.1 K @ 20 °C according to [DIN EN 60751, 1996] class A.
- Humidity: Rotronic HygroClip HC2-C05 sensor with ±1.5 % RH [Rotronic 2009]
- CO_2: Vaisala GMW20, range: 0-5.000 ppm, accuracy ±2 %. Sensors were tuned with 4.000 ppm calibration gas both at ground pressure (~940 hPa for Holzkirchen due to the place's elevation) and low pressure of 755 hPa in the vessel and a pressure correction was derived
- Pumped tubes: samples drawn for 20 and 30 min with flow rates of 0.1 to 1.0 l/min (depending on target compounds) and analysed by GC-MS (gas chromatography - mass spectrometry)
- Flow rate: Schmidt SS20.500 Sensors 0-35 m/s with an accuracy of ±3 % [Schmidt Technology, 2020]

2.2. Test Matrix and sequence

The study investigates four outdoor airflow rates and two occupancy levels: uncongested and fully booked space (Table 1). In order to expose a similar number of subjects to each condition, the uncongested conditions were tested twice while the fully booked condition was tested once. Subjects were only allowed to participate in one test, thus nobody witnessed two conditions. The lower outdoor airflow rates are compensated with increased recirculation airflow rates in order to maintain a constant total flow rate per passenger of 9.4 l/s. The flow rates were adjusted based on the actual count of subjects in the cabin. As a result, the fully booked conditions had a higher total flow rate in the cabin air outlets than the uncongested conditions. Cabin temperature set-point was at 23 °C in order to maintain a thermally comfortable situation. The test matrix was set up under the following considerations:

- **Baseline**: Replication of today's typical CO_2 levels reported in aircraft
- **ASHRAE**: Outdoor airflow rate according to ASHRAE 161 requirement of 3.5 l/s/passenger
- **ASHRAE half:** Half the required outdoor airflow rate (1.8 l/s/passenger)
- **Max. CO_2:** Low outdoor airflow rate to remain below 5.000 ppm limit [FAR part 25, 2005].

Table 1: Test Matrix

Conditions	Baseline	ASHRAE	ASHRAE half	Max. CO_2
Outdoor airflow rate in l/s/passenger	5.2	3.5	1.8	1.1
Recirculation airflow rate in l/s/passenger	4.2	5.9	7.6	8.3
Total airflow rate in l/s/passenger	9.4	9.4	9.4	9.4
Fully booked (~70-80 PAX)	1 session	1 session	1 session	1 session
Uncongested (~35-40 PAX)	2 sessions	2 sessions	2 sessions	2 sessions

The following names will be used for the different test cases: Baseline – uncongested 1 (1. Session), Baseline – uncongested 2 (2. Session), Baseline – fully booked, ASHRAE – uncongested 1 (1. Session), ASHRAE – uncongested 2 (2. Session), ASHRAE – fully booked, ASHRAE half – uncongested 1 (1. Session), ASHRAE half – uncongested 2 (2. Session), ASHRAE half – fully booked, Max. CO_2 – uncongested 1 (1. Session), Max. CO_2 – uncongested 2 (2. Session), Max. CO_2 – fully booked

The test sequence is shown in Figure 2. Subject reception and medical prescreening was 1h before the test started. After boarding, the pressure in the chamber was reduced to 755 hPa. When flight altitude was reached, the desired ventilation regime was set. Subjects answered psychological and health questionnaires and were tested for performance in Test Batteries 1 and 2, and detailed questionnaires on comfort were distributed in the middle and at the end of the session (Comfort Battery). After test battery 2 the cabin was re-pressurized and de-boarding was performed.

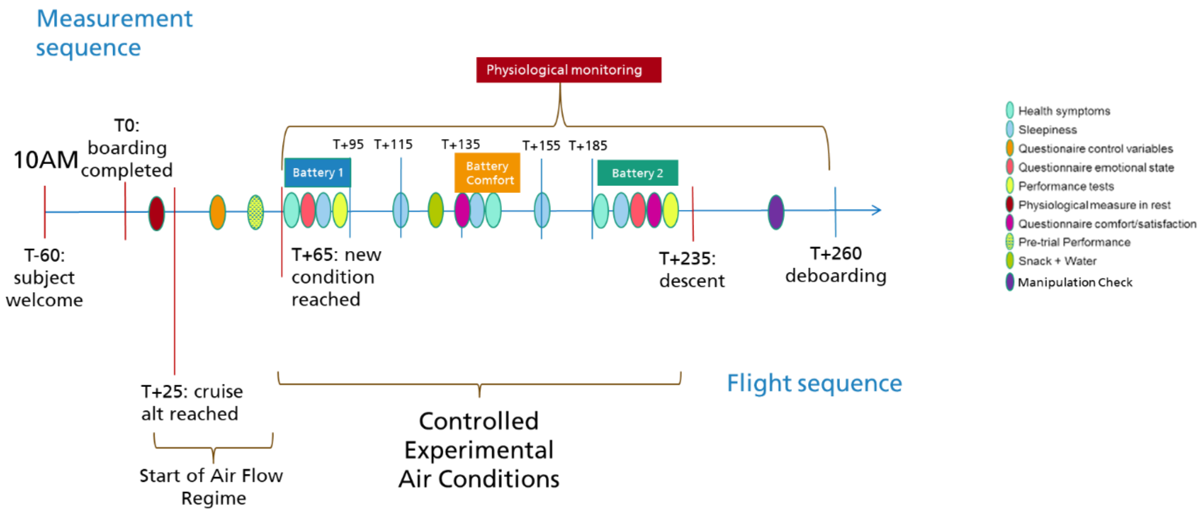

Figure 2: Test sequence

Only low emitting food (pretzels) and water were served to the subjects to not artificially alter the VOC composition in the cabin. Subjects were asked not to consume own food and beverages. In a real flight, coffee, tea, juices and alcoholic drinks may be served as well as food with higher emission. While for the high outdoor airflow rates, these events are expected to be flushed out quickly from the cabin, the low outdoor airflow rates show noticeable transient times and thus the effect of such events would persist longer. Furthermore, engine oils were disregarded in this study as it focused on emissions generated inside the cabin.

2.3. Assessment of air quality

The assessment of the indoor environment was performed by a trained sensory panel according to the requirements of [ISO 16000-30] and subjects' ratings via questionnaire at the end of the session.

For the first test of each condition, a sensory panel consisting of eight trained test persons entered the cabin and assessed the perceived intensity and the hedonic odor tone as well as the odor quality of the cabin air. The hedonic odor tone gives a statement on the extent to which the odor is pleasant or unpleasant whereas the quality rates similarity to known smells (e.g. fatty, citrus, etc.).

Within the set of questionnaires, all subjects were asked to rate the smell in the cabin on a five point scale (How would you assess the odour intensity in this flight? no odour; slight odour; moderate odour; strong odour; overwhelming odour), evaluation of the air quality with a five point Likert scale (How would you rate the air quality in this flight? very poor; poor; average; good; very good/excellent) and the acceptability of the air quality with an approach used by [Wargocki 2001 and Wargocki 2004].

3. Results

3.1. Temperatures

Temperatures were averaged for the entire exposure and for the timeslots the subjects filled out questionnaires (Figure 3). The cabin temperature and stratification usually were around ±1.5 K from the average, therefore only the average temperature in the occupied zone (0-1.1 m height) is reported here. The temperature target of 23 °C was maintained ±1 K. It is assumed that the "ASHRAE fully booked" condition is colder because subjects were close to the control feedback sensor in the cabin and sufficient cooling power to react was available. For the "Max. CO_2 fully booked" condition, the available cooling power of the recirculation heat exchanger came to its limit and therefore temperature in the cabin was higher.

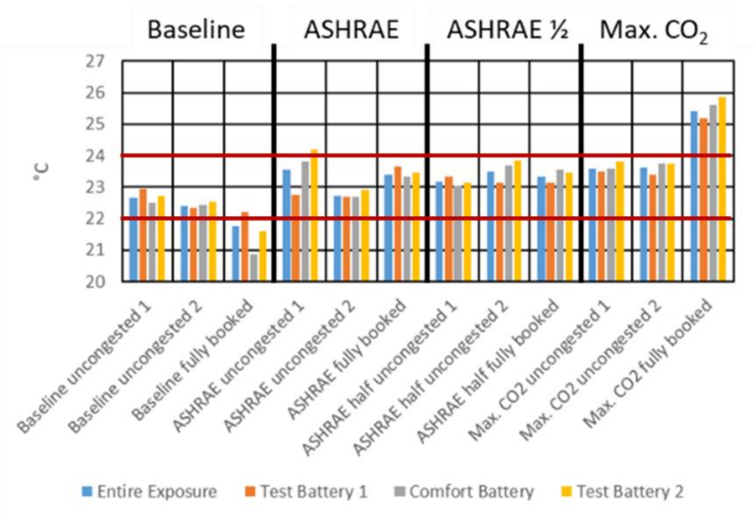

Figure 3: Average cabin temperature

3.2. Cabin Humidity

A clear trend of increased cabin relative humidity with decreasing outside airflow rate is obvious (Figure 4). In the "Baseline" conditions, values around 15% RH are measured that are well in line with other publications [Giacona, 2013]. For the "ASHRAE half" and "Max. CO2" conditions, a gradual increase of relative humidity from test battery 1 over comfort battery to test battery 2 is obvious. Due to the low outside airflow rate, the time constant of the cabin to reach steady-state is higher and thus the build-up phase is longer. Even at the end of the test, an increase in moisture is still obvious. For the fully booked case, the total flow rate was higher, and therefore humidity level was closer to convergence.

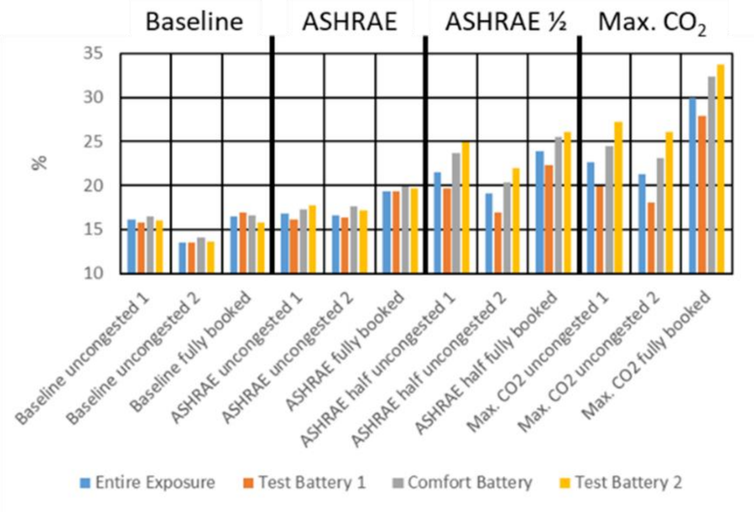

Figure 4: Measured average relative humidity in the cabin

3.3. CO_2 concentration

A clear trend of increased cabin CO_2 concentration with decreasing outside airflow rate is obvious (Figure 5). For the baseline case, the content is ~1.500 ppm (pressure corrected). For the "ASHRAE half" and "Max. CO_2" cases, a gradual increase over the test time is obvious, similar to the findings for relative humidity.

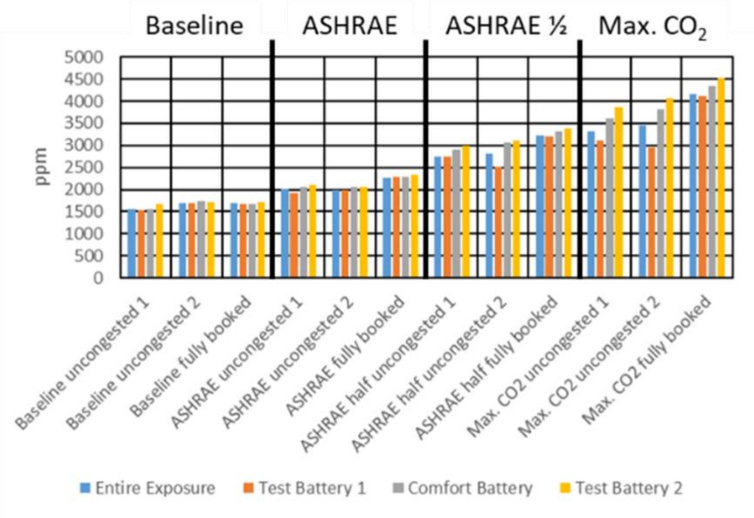

Figure 5: Measured average CO_2 concentration in the cabin (pressure corrected)

3.4. TVOCs

TVOCs determinations were performed by sampling and offline analysis by GC-MS. Results are shown in Figure 6. The general tendency to increased TVOC levels with lower outdoor airflow rate is obvious, however less expressed than for humidity and CO_2. The peak in the "ASHRAE half – fully booked" is due to a peak in ethanol. Even though the subjects were told only to drink water and were observed by the cabin crew, it cannot be excluded that somebody brought alcoholic beverages on board. The peak in the "Max. CO_2 – uncongested 2" condition is due to an event that made it necessary to disinfect the galley with isopropanol cleaning agent during the test conduction. Generally, VOCs are below or within the limits of UBA [Umweltbundesamt 2007] level 2 (300-1.000 µg/m³, "no relevant objections, increased ventilation recommended").

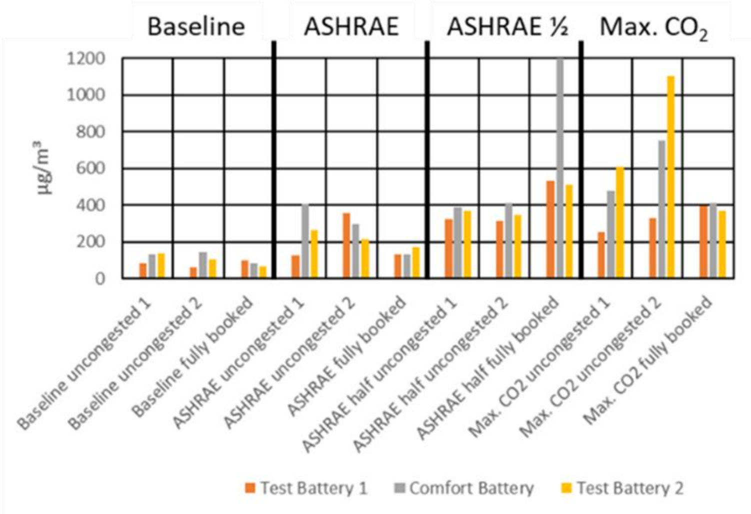

Figure 6: Measured TVOC concentration in the cabin air

3.5. Trained panel and subject votes on air quality

The trained panel was used in the cases "Baseline uncongested 1", "ASHRAE uncongested 1", "ASHRAE half uncongested 1" and "Max. CO_2 uncongested 1". The result shows no clear trend to increased perceived intensity or worse hedonic tone. The votes show a distinct intensity of smell and a slightly unpleasant tone independently from the airflow regime

The subject votes given in questionnaires gives a similar result, mostly no smell or slight smell were voted (>80%). Acceptability was voted >85% for all conditions.

4. Discussion

This paper shows the effect of lower outdoor airflow rate and ventilation based on passenger count on cabin relative humidity, CO_2 concentration and TVOC level. The measurements were taken during a subject study with a randomized controlled design, blinded participants and participants representative of flight passengers with regard to age and sex. Thus, the emitted and measured species should be representative for the flying people.

The measured data for the "Baseline" condition show to realistically replicate humidity and CO_2 levels reported from commercial flights. The TVOC measurement and odour perceptions may be impacted by the used mock-up and the strict behaviour rules for the subjects.

Airflow rates were selected to generate different levels of CO_2. Whether these airflow rates are compatible with other requirements of the aircraft ventilation like e.g. exhaust airflow rates in the lavatories and galley, cabin pressurization, cooling of avionics, etc. has been disregarded.

The general trend, to have a higher satisfaction with the environment despite a similar exposure in the uncongested case was even reported for other comfort parameters in the "Baseline" case, whereas the other three airflow regimes are currently under evaluation [Herbig et al., 2020].

5. Conclusion

This paper presents the indoor air measurements for different outdoor airflow rates in a realistic cabin mock-up with subjects in a simulated flight. The major results are:

- Relative humidity, CO_2 and TVOC clearly increase with decreasing outdoor airflow rate
- Singular effects like an ethanol or cleaning agent event showed higher impact on the TVOC levels than the airflow regime
- Neither a trained sensory panel nor subjects could differentiate smell or acceptability for the different airflow conditions.

More detailed analysis on subjects comfort and wellbeing as well as performance is ongoing and will be disseminated in upcoming publications.

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The authors are responsible for the content of this publication.

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