

Letters

RESEARCH LETTER

Experimental Assessment of Carbon Dioxide Content in Inhaled Air With or Without Face Masks in Healthy Children: A Randomized Clinical Trial

Many governments have made nose and mouth covering or face masks compulsory for schoolchildren. The evidence base for this is weak.^{1,2} The question whether nose and mouth covering increases carbon dioxide in inhaled air is crucial. A large-scale survey³ in Germany of adverse effects in parents and children using data of 25 930 children has shown that 68% of the participating children had problems when wearing nose and mouth coverings.

The normal content of carbon dioxide in the open is about 0.04% by volume (ie, 400 ppm). A level of 0.2% by volume or 2000 ppm is the limit for closed rooms according to the German Federal Environmental Office, and everything beyond this level is unacceptable.⁴

Methods | We measured carbon dioxide content in inhaled air with and without 2 types of nose and mouth coverings in a well-controlled, counterbalanced, short-term experimental study in volunteer children in good health (details are in the eMethods in Supplement 1). The study was conducted according to the Declaration of Helsinki and submitted to the ethics committee of the University Witten/Herdecke. All children gave written informed consent, and parents also gave written informed consent for children younger than 16 years. A 3-minute continuous measurement was taken for baseline carbon dioxide levels without a face mask. A 9-minute measurement for each type of mask was allowed: 3 minutes for measuring the carbon dioxide content in joint inhaled and exhaled air, 3 minutes for measuring the carbon dioxide content during inhala-

tion, and 3 minutes for measuring the carbon dioxide content during exhalation. The carbon dioxide content of ambient air was always kept well under 0.1% by volume through multiple ventilations. The sequence of masks was randomized, and randomization was blinded and stratified by age of children. We analyzed data using a linear model for repeated measurements with $P < .05$ as the significance threshold. The measurement protocol (trial protocol in Supplement 2) is available online.⁵ Data were collected on April 9 and 10, 2021, and analyzed using Statistica version 13.3 (TIBCO).

Results | The mean (SD) age of the children was 10.7 (2.6) years (range, 6-17 years), and there were 20 girls and 25 boys. Measurement results are presented in the Table. We checked potential associations with outcome. Only age was associated with carbon dioxide content in inhaled air ($y = 1.9867 - 0.0555 \times x$; $r = -0.39$; $P = .008$; Figure). Hence, we added age as a continuous covariate to the model. This revealed an association (partial $\eta^2 = 0.43$; $P < .001$). Contrasts showed that this was attributable to the difference between the baseline value and the values of both masks jointly. Contrasts between the 2 types of masks were not significant. We measured means (SDs) between 13 120 (384) and 13 910 (374) ppm of carbon dioxide in inhaled air under surgical and filtering facepiece 2 (FFP2) masks, which is higher than what is already deemed unacceptable by the German Federal Environmental Office by a factor of 6. This was a value reached after 3 minutes of measurement. Children under normal conditions in schools wear such masks for a mean of 270 (interquartile range, 120-390) minutes.³ The Figure shows that the value of the child with the lowest carbon dioxide level was 3-fold greater than the limit of 0.2 % by volume.⁴ The youngest children had the highest values, with one 7-year-old child's carbon dioxide level measured at 25 000 ppm.

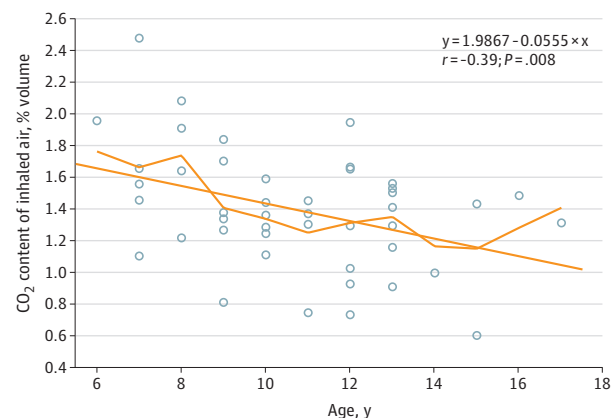
Table. Carbon Dioxide Values Under Various Conditions

Measurement	Participants, No.	Carbon dioxide, % by volume	
		Mean (SD) [95% CI]	Range
Baseline			
Pretest	45	0.268 (0.108) [0.235-0.300]	0.100-0.628
Posttest ^a	39	0.281 (0.105) [0.247-0.316]	0.100-0.525
Main outcome			
Inhaled air with surgical mask	45	1.312 (0.384) [1.197-1.427]	0.577-2.554
Inhaled air with FFP2 mask	45	1.391 (0.374) [1.279-1.504]	0.600-2.475
Additional outcome			
Joint exhaled and inhaled air with surgical mask	45	2.650 (0.486) [2.504-2.796]	1.33-3.41
Exhaled air with surgical mask	44	3.847 (0.678) [3.641-4.053]	1.783-4.754
Joint inhaled and exhaled air with FFP2 mask	45	2.677 (0.386) [2.561-2.793]	1.660-3.418
Exhaled air with FFP2	45	3.846 (0.547) [3.682-4.011]	2.592-5.24
Carbon dioxide content in ambient air	NA	0.074 (0.003) [0.073-0.075]	0.067-0.083

Abbreviations: FFP, filtering facepiece; NA, not applicable.

^a Posttest scores were missing in 6 children because they stopped the measurement after wearing the masks.

Figure. Scatterplot of Carbon Dioxide Content in Inhaled Air Under Filtering Facepiece Mask by Age



Linear regression line with locally weighted scatterplot smoothing.

Discussion | The limitations of the study were its short-term nature in a laboratory-like setting and the fact that children were not occupied during measurements and might have been apprehensive. Most of the complaints reported by children³ can be understood as consequences of elevated carbon dioxide levels in inhaled air. This is because of the dead-space volume of the masks, which collects exhaled carbon dioxide quickly after a short time. This carbon dioxide mixes with fresh air and elevates the carbon dioxide content of inhaled air under the mask, and this was more pronounced in this study for younger children.

This leads in turn to impairments attributable to hypercapnia. A recent review⁶ concluded that there was ample evidence for adverse effects of wearing such masks. We suggest that decision-makers weigh the hard evidence produced by these experimental measurements accordingly, which suggest that children should not be forced to wear face masks.

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