Chest Compression Duration May Be Improved When Rescuers Breathe Supplemental Oxygen

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BACKGROUND: At sea level, performing chest compressions is a demanding physical exercise. On a commercial flight at cruise altitude, the barometric pressure in the cabin is approximately equal to an altitude of 2438 m. This results in a P_{O_2} equivalent to breathing an F_IO_2 of 15% at sea level, a condition under which both the duration and quality of cardiopulmonary resuscitation (CPR) may deteriorate. We hypothesized that rescuers will be able to perform fewer rounds of high-quality CPR at an F_IO_2 of 15%.

METHODS: In this crossover simulation trial, 16 healthy volunteers participated in 2 separate sessions and performed up to 14 2-min rounds of chest compressions at an F_IO_2 of either 0.15 or 0.21 in randomized order. Subjects were stopped if their S_pO_2 was below 80%, if chest compression rate or depth was not achieved for 2/3 of compressions, or if they felt fatigued or dyspneic.

RESULTS: Fewer rounds of chest compressions were successfully completed in the hypoxic than in the normoxic condition, (median [IQR] 4.5 [3,8.5]) vs. 5 [4,14]). The decline in arterial S_pO_2 while performing chest compressions was greater in the hypoxic condition than in the normoxic condition [mean (SD), 6.19% (4.1) vs. 2% (1.66)].

DISCUSSION: Our findings suggest that the ability of rescuers to perform chest compressions in a commercial airline cabin at cruising altitude may be limited due to hypoxia. One possible solution is supplemental oxygen for rescuers who perform chest compressions for in-flight cardiac arrest.

KEYWORDS: CPR, chest compressions, hypoxia, cardiopulmonary resuscitation, cardiac arrest, travel medicine, in-flight medical emergency.

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Each day eight million passengers fly on a commercial airline flight, and approximately 130 will experience a cardiac arrest.[6] High-quality cardiopulmonary resuscitation (CPR) is a key component to successful return of circulation after cardiac arrest. The difficulty of resuscitation, however, may vary by location.[1,2,22] At cruising altitude, the barometric pressure inside the cabin of a transport-category airplane (defined as a jet aircraft with more than 10 seats or a propeller-driven aircraft with more than 19 seats) is equivalent to that of an altitude between 1829 to 2438 m (6000–8000 ft). Even though the fraction of inspired oxygen (F_IO_2) is 0.21, the decreased barometric pressure results in an effective F_IO_2 at sea level of 0.15.[16,20]

Nearly 321,000 patients in the United States experience an out-of-hospital cardiac arrest (OHCA) each year. The rate of survival to hospital discharge is less than 10%.[15] Factors associated with improved outcomes after out-of-hospital cardiac arrest include a witnessed arrest with bystander cardio-pulmonary resuscitation (CPR), the availability of an automated external defibrillator (AED), and access to advanced life support. Effective CPR, which includes prompt, sustained chest compressions,[11] is the best predictor of survival after out-of-hospital cardiac arrest with a nonshockable rhythm.

Effective CPR requires significant physical exertion on the part of the rescuer.[8] Observations that increasing the number of chest compressions within a set time period leads to earlier rescuer fatigue suggests that aerobic capacity may limit the ability

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of a rescuer to perform prolonged, high quality CPR[12] and that the mild hypoxemia experienced during a commercial airline flight may further limit effective chest compressions. If so, administering supplemental O_2 to the rescuer during an in-flight cardiac arrest may facilitate more effective chest compressions. We hypothesized that rescuers will be able to perform more rounds of high-quality chest compressions when breathing a gas mixture equivalent to room air at sea level than when breathing a gas mixture that simulates the F_IO_2 in a commercial aircraft cabin at cruising altitude.

METHODS

Subjects

This blinded, within-subjects crossover simulation trial was approved by the University of Chicago IRB (IRB19-0535) and registered with ClinicalTrials.gov (NCT04072484). Each subject provided written informed consent before participating.

We recruited a convenience sample of subjects. Inclusion criteria were healthy individuals over 18 yr of age who were trained in cardiopulmonary resuscitation. Exclusion criteria were the self-reported inability to perform the equivalent of 4 metabolic equivalents (mets) of exercise, living at an altitude higher than 600 ft above sea level, traveling by air within the 3 d immediately preceding the study, or traveling to an altitude of higher than 1000 ft above sea level during the 2 wk immediately preceding the study. Subjects were also excluded if they had any medical condition that would prevent the performance of chest compressions or flying on a commercial airline flight, such as coexisting heart or lung disease or a baseline S_pO_2 of $< 95\%$ (see **Appendix A** https://doi.org/10.3357/AMHP.5698sd.2020). Subjects were also asked to refrain from strenuous exercise such as running or weightlifting for 12 h before each trial.

Procedure

Subjects were screened for exclusion criteria. Each subject filled out a prestudy survey. Subjects were instructed both verbally and in writing to stop chest compressions if they felt fatigued, lightheaded, or short of breath. We defined fatigue as 'more tired than you would feel during regular exercise' and shortness of breath as 'breathing harder than you would during regular exercise.' All study procedures occurred at the University of Chicago in Hyde Park, Chicago, IL, at an elevation near sea level (181 m) in an empty conference room.

Subjects underwent both study conditions (F_IO_2 21%, F_IO_2 15%) in random order on separate days at least 2 d apart, with one condition occurring per day. The order of conditions was randomized using a random number generator (https://stattrek.com/statistics/random-number-generator.aspx#error). Both sessions were conducted in identical form. Chest compressions were performed on a Little Anne QCPR mannequin (Laerdal, Wappingers Falls, NY), which is designed to evaluate CPR quality in compliance with American Heart Association guidelines, and that delivers an audible 'click' when the correct chest compression depth is reached.[4] Quality of chest compressions was monitored using Laerdal's Quality Cardiopulmonary Resuscitation (QCPR) instructor mobile application for iPhone (Apple, Cupertino, CA).

At the start of each session, baseline S_pO_2 and heart rate were measured prior to starting chest compressions. Practice chest compressions were performed for 2 min, during which subjects received feedback on compression depth, rate, and recoil. Subjects who were not able to perform compressions with adequate depth, rate, or recoil after coaching were excluded at this point. Subjects were next acclimated to the condition by wearing a face mask and breathing the assigned gas mixture for 5 min while at rest. The face mask covered the nose and mouth and was attached via a plastic hose to a reduced oxygen breathing device (ROBD, Everest Summit II Altitude Generator, Hypoxico, New York, NY). The ROBD and oxygen analyzer were positioned so that subjects could not see their settings.

After acclimation, subjects performed up to 14 2-min rounds of continuous chest compressions while wearing the face mask and breathing the gas mixture, which is consistent with the Universal Guidelines for Termination of cardiopulmonary resuscitation.[7] Compressions were not interrupted for rescue breaths and no feedback on quality of compressions was provided during this portion of the study. Subjects took a 10 s break between each round to simulate the pulse and rhythm check that occurs during CPR. During this 10 s break, the subject's S_pO_2 and HR were measured, and the subject was asked if he or she felt fatigued, lightheaded, or short of breath.

CPR was halted and the session was ended if the American Heart Association's guideline threshold[11] of a depth of 5–6 cm or a rate of at least 100–120 compressions/minute as measured on the QCPR instructor application was not met during at least 66% of chest compressions during a given 2-min period. The session was also ended if the subject became fatigued, lightheaded, or dyspneic, if the subject's measured S_pO_2 was less than 80% at any time, or after 14 rounds of chest compressions were completed. Incomplete rounds were scored as not successful. After completing CPR, subjects removed the mask and their S_pO_2 and HR were measured again. The poststudy survey was then completed on each day of testing. The subject was allowed to leave the study area after S_pO_2 and HR returned to baseline.

Statistical Analysis

Our primary outcome was the number of successfully completed 2-min rounds of CPR in each condition (14 possible total rounds). Our secondary outcomes were differences in S_pO_2 in each arm after equilibration to the mask and after performing chest compressions. A Bonferroni adjustment was used to account for multiple secondary outcomes.

The sample size was calculated based on our primary outcome measure. In a 2007 study of the effect of hypoxia on exercise performance, time to exhaustion was reduced by two-thirds (4.2 ± 0.5 min at a F_IO_2 of 0.13 as compared to 13.4 ± 0.8 min under normoxic conditions).[19] We anticipated that chest compressions would be as strenuous as vigorous exercise and would produce a similar level of exhaustion, and that the effect of hypoxia in this study would be similar.

We then used the decrease in exercise tolerance under hypoxic conditions in the 2007 study to calculate the sample size for the current study.[19] Presumably, the number of successful 2-min CPR rounds completed would increase by 2/3 (increase from 2 to 6 out of 14 possible rounds) when subjects were exposed to the normoxia condition as compared to the hypoxia condition. We thus used this assumption and McNemar's test to calculate that 29 subjects would be needed to achieve a 66% reduction in unsuccessful rounds, assuming alpha = 0.05, beta = 0.8.

R was used for data analysis.[18] Normality of distribution was assessed using the Shapiro-Wilk test. We used the Wilcoxon-Signed Rank test for nonnormally distributed data and *t*-tests for normally distributed data.

RESULTS

On March 16th 2020, the University of Chicago halted all research in response to the COVID-19 pandemic. At that time, 16 subjects (6 men, 10 women, ages 19–33, median = 21, interquartile range [20,22]) had completed both conditions (**Fig. 1**). An interim data analysis at this time suggested that we had achieved statistical significance for our primary and secondary outcomes. Data is publicly available in the Figshare data repository at: https://doi.org/10.6084/m9.figshare.12192231.

In the normoxic arm of the study, 10 subjects stopped due to fatigue, 6 completed all 14 rounds, none were halted by the investigators for hypoxia, and none were halted for inadequate CPR quality. The median number of rounds for subjects who stopped due to fatigue in the normoxic arm was 5 [2.5,5] (median [IQR]). In the hypoxic arm of the study, 2 completed all 14 rounds, 12 subjects stopped due to fatigue, 2 were halted by the investigators when their S_pO_2 fell below 80%, and none were halted for inadequate CPR quality (**Table I**). The median number of rounds for subjects who stopped due to fatigue in the hypoxic arm was 4 [3,7] (median [IQR]). Overall, more rounds of chest compressions were successfully completed in the normoxic than in the hypoxic condition (median [IQR] 5 [4,14] vs. 4.5 [3,8.5]), $P = 0.04$, V = 65.5, Wilcoxon-Signed Rank test) (Table I). A Bonferroni analysis for multiple secondary outcomes showed a significance level of $P = 0.017$.

After equilibration to the mask and prior to starting chest compressions, S_pO_2 was higher in the normoxic than the hypoxic condition [mean (SD) 97.5% (0.79) vs. 92.8% (2.58), $P < 0.001$, t = -7.28, two-tailed *t*-test] (Table I). The lowest S_pO_2 measured after performing chest compressions was higher during the normoxic than the hypoxic condition [mean (SD) 95.5% (1.77) vs. 86.6% (4.66), $P < 0.001$, t = -9.07, two-tailed *t*-test]. The lowest S_pO_2 measured across all subjects was 92% in the normoxic condition and 77% in the hypoxic condition (Table I). S_pO_2 declined in 26 of 32 sessions between the start of the condition and the lowest value recorded after performing chest compressions. This decline was greater in the hypoxic than the normoxic condition, (mean (SD) 6.19% (4.1) vs. 2% (1.66), $P < 0.001$, t = 4.70, two-tailed *t*-test) (Table I). Of the 16 subjects, 12 demonstrated frank hypoxemia ($S_pO_2 < 90\%$) when performing chest compressions in the hypoxic condition.

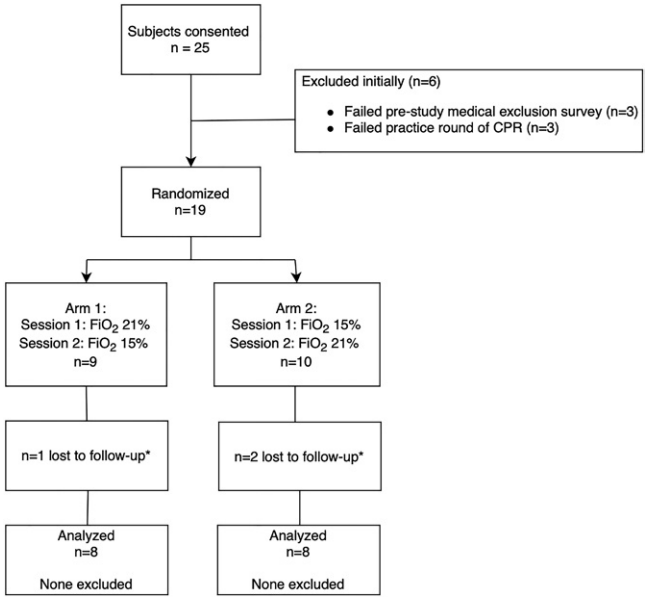

Fig. 1. Study flow diagram. *Subjects lost to follow-up because research was halted at the University of Chicago because of the COVID-19 crisis.

At the end of the second session, subjects were asked to give a numeric ranking for the question 'How difficult was it to perform chest compressions wearing a face mask' on a scale of 0 = not at all difficult to 100 = very difficult. The overall ranking was 30.9 (26), mean (SD). The ranking for the group randomized to begin with the normoxic condition, 32.5 (19.8), was not different than the ranking for the group randomized to the hypoxic condition, 29.4 (33.9), mean (SD), two-tailed *t*-test, $P = 0.79$.

DISCUSSION

In this crossover simulation study of chest compression performance during hypoxic and normoxic conditions, we found that subjects who breathed a gas mixture with an F_IO_2 of 0.15 had a lower oxygen saturation at baseline, a greater decline in S_pO_2 during CPR, and a lower "nadir" S_pO_2. Of the 16 subjects, 12 were frankly hypoxemic while breathing the hypoxic gas mixture during CPR. Performance of chest compressions was worse during the hypoxic condition, and subjects performed fewer rounds of high-quality CPR.

Our findings are consistent with existing data. A 2020 simulation study of chest compressions performed at 11,332 ft above sea level by experienced Austrian Mountain Rescue Service mountaineers found no changes in time to exhaustion but did note a decrease in the depth of chest compressions at the higher altitude.[8] Although our study found a decrease in duration of chest compressions, this effect may have been due to differences in fitness levels between subjects in our study and the above. Other studies of CPR at altitude have found increases in the perception of effort with no change in quality,[5] lower quality and greater fatigue,[23] and fatigue and desaturation in the rescuers.[18]

Table I. Rounds of CPR Completed, Initial S_pO_2, and Lowest S_pO_2.

			F_IO_2 21%			F_IO_2 15%		
Subject #	Age	Baseline S_pO_2	# of Rounds Completed	S_pO_2 at start of condition	Lowest S_pO_2	# of Rounds Completed	S_pO_2 at start of condition	Lowest S_pO_2
1	20	98	5	97	96	4	95	87
2	20	99	5	97	97	5	93	93
3	21	98	5	96	95	3	91	90
4	21	98	5	99	97	3	97	91
5	21	98	12	98	93	7	92	84
6	22	97	14	98	95	14	94	87
7	20	98	3	97	97	1	96	89
8	21	98	2	98	98	1	97	94
9	33	98	14	98	96	7	92	89
10	20	98	4	98	97	9	92	84
11	20	97	1	98	98	3	91	88
12	20	97	4	97	95	4	88	79
13	35	98	14	97	92	7	95	84
14	22	97	14	98	95	9	89	89
15	23	98	14	96	93	14	91	81
16	22	98	14	98	94	1	92	77

The pressure altitude in the cabin of a transport-category airplane may depend on both cruise altitude and the specific aircraft type. Although the cabin pressure altitude in the majority of transport-category aircraft is 2438 m/8000 ft (corresponding to an F_IO_2 of 0.15), the pressure altitude is somewhat lower in the Boeing 787 and the Airbus A350 and A380 aircraft (1829 m/6000 ft) where the F_IO_2 is 0.16%. Studies more closely approximating our altitude conditions also found a decrease in oxygen saturation and an increase in fatigue at altitude.[5,17,23] Our study differs from these in limiting the intervention to F_IO_2 alone, recruiting subjects without prior endurance training, and allowing for up to 30 min of chest compressions with a 10-s pause every 2 min. This more closely approximates the level of fatigue associated with CPR as it may be administered by a crewmember or volunteer rescuer during a commercial airline flight.[14]

Our findings are also generally consistent with prior data on the effect of hypoxic conditions on exercise tolerance. A 1998 review of exercise performance during competitive sporting events at altitude found exercise impairment proportional to both exercise duration and elevation but no effect on muscle strength, maximal muscle power, or anaerobic performance.[9] Our findings suggest a greater limitation on aerobic activity under hypoxic conditions. A 2007 study of men engaged in competitive endurance sports tested quadriceps force output under hypoxic conditions and found decreases in evoked force output under hypoxic conditions but not at the point of exhaustion.[10] Our finding that the duration of chest compressions was decreased while breathing a hypoxic gas mixture is consistent with this finding.

Although the mechanisms underlying a decrease in duration and quality of tasks involving aerobic exercise are unknown, both peripheral (muscle fatigue due to oxygen supply reduction)[21] and central (limitation of motor neuron output to protect homeostasis)[13] causes have been described. Regardless, limitations in volitional exercise tolerance are a consistent observation across the literature and in our study.

The results of our study have potential implications for the conduct of CPR during airline flights. In addition to a lower F_IO_2, factors that affect CPR during commercial aviation include a cramped cabin environment, a patient with an unknown medical history, and a potentially limited availability of rescuers. In light of these issues, the effects of any decrease in the duration and quality of chest compressions may be exacerbated. The normoxic condition in our study approximates the P_aO_2 of a rescuer on a transport-category aircraft who wears a face mask that provides $4\ L \cdot min^{-1}$ of oxygen, and our findings suggest that this improves the quality and duration of chest compressions. This suggests that one possible solution is to administer supplemental oxygen to those who perform chest compressions during in-flight CPR. If a rescuer chose to use a higher flow of supplemental oxygen, the conditions may potentially be even better than those used in our study. Another option would be to shorten the recommended time before switching rescuers during in-flight CPR to allow for the increased fatigue rescuers are likely to feel under hypoxic conditions, subject to the availability of additional volunteers.

Our study has several limitations: because our study was halted prematurely, our sample size was smaller than originally intended. It is possible that we would have seen a larger effect with our originally intended sample size. The majority of our study subjects were undergraduate college students, and all were under 35 yr of age with no coexisting medical problems. Our study population is therefore younger and healthier than the flying public, possibly leading us to underestimate the effect of hypoxemia on older or less healthy rescuers.

We also used a facemask, which would not be typically worn during chest compressions and may have contributed to perceptions of rescuer fatigue. Subjects wore the same mask during both conditions, however, and rated it as not overly burdensome during a poststudy survey. Another confounder may be that the subjects were more familiar with performing chest compressions on the second session, but all subjects had already had CPR training and the order of sessions was randomized. We also relied on self-reports to screen subjects for living at

sea-level altitude, lack of recent travel to high-altitude locations, being able to generate 4 metabolic equivalents (METS) of exercise activity, and having refrained from vigorous physical activity prior to testing.

Although current guidelines suggest switching rescuers every 2 min, our simulation had only one rescuer performing chest compressions. Our study design, using one rescuer, may however mirror conditions that might realistically be seen in the cramped space and limited resources of a transport-category aircraft. Finally, we did not directly measure blood oxygen saturation, and relied instead on noninvasive pulse oximetry. Pulse oximetry only accurately estimates S_pO_2 with a mean error of 2% during exercise in hypoxic conditions.[3] However, the difference we observed between the hypoxic and normoxic conditions was greater than 2%.

CONCLUSION

We found that subjects exposed to a F_IO_2 that approximates the PO_2 experienced by passengers during a commercial airline flight became fatigued more quickly and performed poorer quality chest compressions than they did under normoxic conditions. Providing the rescuer with supplemental oxygen during CPR on commercial airline flights may increase the likelihood of sustained high-quality chest compressions. Additional research is needed to determine which rescuers would benefit most from breathing supplemental oxygen during CPR as well as the ideal F_IO_2 to provide to the rescuer.

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