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# Cardiorespiratory dynamics of rescuers during cardiopulmonary resuscitation in a hypoxic environment☆

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ABSTRACT

*Objective:* We had previously experienced a case involving prolonged cardiopulmonary resuscitation (CPR) on Mt. Fuji (3776 m), demanding strenuous work by the rescuers. The objective of this study was to compare the effect of compression-only and conventional CPR on oxygen saturation of rescuers in a hypoxemic environment.
*Methods:* Changes in percutaneous arterial oxygen saturation ($SpO_2$) and heart rate during CPR action were measured in a hypobaric chamber with barometric pressure adjusted to be equivalent to 3700 m above sea level (630–640 hPa). Thirty-three volunteers performed CPR with or without breaths using a CPR mannequin.
*Results:* In a 3700-m-equivalent environment, $SpO_2$ was reduced only when CPR was performed without breaths ($P < .05$, one-way analysis of variance (ANOVA) post hoc Tukey test). Heart rate increased during CPR regardless of the presence or absence of breaths. Mean scores on the Borg scale, a subjective measure of fatigue, after CPR action in the 3700-m-equivalent environment were significantly higher ($15 \pm 2$) than scores after CPR performed at sea level ($11 \pm 2$, $P < .01$, paired *t*-test). No lethal dysrhythmia was found in subjects with a wearable electrode shirt.
*Conclusions:* Prolonged CPR at high altitude exerts a significant physical effect upon the condition of rescuers. Compression-only CPR at high altitude may deteriorate rescuer oxygenation, whereas CPR with breaths might ameliorate such deterioration.



## 1. Introduction

Growing numbers of individuals with cardiovascular disease are ascending to high altitude [1-3]. Immediate cardiopulmonary resuscitation (CPR) is required in patients with cardiac arrest [4,5]. However, performance of CPR is effort-intensive even at sea level, and CPR at altitude is even more exhausting [6-8].

We encountered a case of prolonged CPR at high altitude, in which a rescuer performed prolonged CPR in an out-of-hospital setting on an individual following a suspected cardiac or neurological event, with an unsuccessful outcome. The rescuer, who continued CPR during steep mountain transportation even though CPR in the lopsided, narrow carriage was very difficult, was exhausted after the work [8]. Following the above-mentioned actions, we conducted research to clarify the physical condition of rescuers after performing CPR at high altitudes, and reported that the work of CPR has a significant impact on the physiological parameters of participants [8].

The most recent American Heart Association Guideline mentioned that compression-only CPR is simpler for lay providers to learn than conventional CPR (compressions with breaths), and can even be coached by a dispatcher during an emergency. It also stated that public education on compression-only CPR promoted both overall CPR and compression-only CPR by bystanders [9]. Conversely, the opinion has been put forward that compression-only CPR is more exhausting than conventional CPR. Nishiyama et al. reported that chest compressions to an appropriate depth decreased more rapidly during chest compression-only CPR due to fatigue [10]. We hypothesized that conventional CPR may be better than compression-only CPR for oxygen saturation of rescuers especially at high altitude. This was because we expected that deep breaths prior to blowing into the victim and the action of blowing against expiratory resistance (resistance of the airways and lungs of the victim) may have better effects on the respiratory physiology of rescuers during conventional CPR. Although rescuers holding their breath during compression-only CPR have not been reported, a past study showed that percutaneous arterial oxygen saturation ($SpO_2$) tended to decrease when holding the breath, particularly at high altitude [11].

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The present study measured arterial oxygen saturation and heart rate (HR) among subjects performing CPR in a simulation chamber with barometric pressure adjusted to 630–640 hPa (equivalent to 3700 m above sea level; a.s.l.). Initially, data acquisition at the top of Mt. Fuji was planned, and we actually obtained data from three subjects before realizing that performing such a study was rather difficult. This was because the physical wellness of subjects was not uniform following the physical workload of climbing. In addition, stabilizing the environmental conditions in the mountain hut for a long duration was expensive and time-consuming. Furthermore, if volunteers had developed physical problems, evacuation from the summit of Mt. Fuji would have likely proven difficult. For such reasons, we undertook data acquisition in a hypobaric, hypoxic chamber designed for performing "high-altitude training" at low altitude. This research framework was expected to obtain more standardized data and scientifically solid evidence.

## 2. Methods

### *2.1. Study subjects*

Approval of the local human ethics committee (Gunma University Research Ethics Committee for Human Studies No. 20-20) was obtained before this study, and the study protocol was registered to an internationally accessible clinical research registration site (UMIN; UMIN000020659).

This study was conducted in a hypobaric chamber with barometric pressure adjusted to be equivalent to 3700 m a.s.l. (630–640 hPa). The chamber was situated 80 m a.s.l. To compare the effects of compression-only and conventional CPR on oxygen saturation in rescuers at low altitude as well, measurements were also made outside the chamber while all participants performed compression-only and conventional CPR. Since we posted information on the research at hospitals, fire departments, and mountain associations, participants mainly comprised medical personnel. The inclusion criteria for this study were healthy individuals ≥20 years old who had completed a Basic Life Support (BLS) and CPR training course (adapted according to International Liaison Committee on Resuscitation guidelines) prior to this study. Potential participants with respiratory and/or circulatory abnormalities, with a history of pneumothorax, or who could not clear their ears were excluded from the study. No subjects were involved in any regular physical exercise regimen, and none had been exposed to altitudes over 2000 m during the half-year prior to the CPR practice in this study. All subjects passed pre-study health check-ups, including chest X-ray, electrocardiography, and laboratory blood tests.

### *2.2. Study protocol and equipment used in the study*

All participants performed compression-only and conventional CPR both inside and outside the hypobaric hypoxic chamber. Both inside and outside the chamber, compression-only and conventional CPR procedures were sequentially repeated twice for a total of 4 cycles, and the duration of each mode was 2 min for each cycle. CPR was always started from compression-only mode. Up to 3 subjects entered the chamber at the same time, and performed CPR one by one. Since 20 min was required for the chamber to decompress and pressurize, participants stayed in the chamber for about 1 h.

The volume of the chamber was 4.8 $m^3$ and the internal pressure was controlled by a pump (FMS O2-CHAMBER; Medical Technology System; Isesaki, Japan). An oxygen cylinder was prepared in the chamber so that participants could interrupt CPR at any time and breathe supplemental oxygen if necessary. Pressure, temperature and relative humidity were set at 630–640 hPa, 18–22 °C, and 40–60%, respectively. The carbon dioxide concentration in the chamber was monitored and kept below 5000 ppm by continuously ventilating the inside space. At least one doctor, nurse, or paramedic was always present in the chamber to provide immediate response in the event of an emergency. Participants always inhaled 100% oxygen through a face mask for 2 min after CPR practice inside the chamber to facilitate recovery.

CPR was performed continuously as a single-operator procedure according to the 2015 American Heart Association (AHA) Guidelines [9] using a transportable CPR trainer (MiniAnne; Laerdal Japan, Tokyo, Japan). The rate of chest compressions was kept constant at 100 compressions/min using a digital quartz metronome (CN89; Yamaha Musical Trading, Tokyo, Japan). The adequacy of chest compressions was monitored by measuring chest balloon pressures using a pressure gauge (CE0123; VBM, Sulz, Germany) connected to the balloon inflating valve. Participants were advised to attain a peak chest balloon pressure of 30–50 $cmH_2O$ with each compression. This pressure value was determined by observing that a 4- to 5-cm chest compression on the simulator model produced results within this pressure range on the gauge (the depth of chest compression recommended in the 2015 AHA Guideline is 5–6 cm [9]). During CPR with breaths, the adequacy of breathing was monitored by observing full inflation of the simulated lung. A compression:ventilation ratio of 30:2 was used, in accordance with the 2015 AHA Guideline.

We used a motion-resistant oximeter probe (Radical 7; MASIMO Japan, Tokyo, Japan) for measuring $SpO_2$ that was always positioned on a finger, because an earlier pilot test had shown that measurement during CPR was more stable with the probe on the index or middle finger than on an ear or toe. HR and arterial blood oxygen saturation were recorded every 15 s.

In some participants, electrocardiograms were also measured in the simulation chamber using a 10-lead wearable electrode shirt for monitoring serious cardiac events. We are developing this smart shirt, which uses dry electrodes and is made with an additive printing method using a stretchable conductive paste with silver filler loading [12,13].

Borg scale scores were collected immediately after each CPR activity [14]. Although the applicability of this scale to situations at high altitude has not yet been confirmed, this simple scale of perceived exertion has often been used to regulate exercise intensity. A higher Borg scale score indicates a subjective feeling of greater physical intensity.

### *2.3. Statistics*

To calculate the sample size, we referred to our previous study in which mean $SpO_2$ recorded at 3700 m a.s.l. was $80 \pm 7\%$ [8]. In the present study, a sample size of 28 subjects was calculated as necessary to achieve 80% power to detect a difference between compression-only and conventional CPR with a significance level of $P < .05$. In accordance with this power analysis and assuming a 10% dropout rate, 33 subjects were enrolled in the study. All data are expressed as mean ± SD, unless otherwise specified. Statistical comparisons of measured values were assessed by repeated-measures one-way analysis of variance (ANOVA) followed by the post-hoc Tukey test or paired *t*-test, using SigmaPlot 13 statistical software (Systat Software, San Jose, CA). Values of $P < .05$ were considered statistically significant.

## 3. Results

Participants comprised 24 male and 9 female volunteers (mean age, 36 ± 9 years; range 20–58 years, height 167 ± 5 cm, weight 59 ± 6 kg). All subjects were able to complete the total of 8 min of CPR tasks as required. Although no lethal dysrhythmia was observed on electrocardiography, a few participants showed insignificant arrhythmias, including premature atrial contraction and premature ventricular contraction.

HR and $SpO_2$ in participants measured inside and outside the hypobaric hypoxic chamber are shown in Fig. 1. HR significantly increased throughout CPR compared to that before CPR, both inside and outside the chamber (Fig. 1A, one-way ANOVA post hoc Tukey test). Comparing the same time points, HR was greater inside the chamber

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