PHYSIOLOGICAL DEMANDS OF QUALITY CARDIOPULMONARY RESUSCITATION PERFORMED AT SIMULATED 3250 METERS HIGH. A PILOT STUDY

Simulated CPR & Altitude

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ABSTRACT

Aim: To analyze the effect of oxygen fraction reduction (O2 14%, equivalent to 3250m) on Q-CPR and rescuers' physiological demands.

Methodology: A quasi-experimental study was carried out in a sample of 9 Q-CPR proficient health care professionals. Participants, in teams of 2 people, performed 10 minutes CPR on a Laerdal ResusciAnne mannequin (30:2 compression/ventilation ratio and alternating roles between rescuers every 2 minutes) in two simulated settings: T21-CPR at sea level (FiO2 of 21%) and T14 – CPR at 3250m altitude (FiO2 of 14%). Effort self-perception was rated from 0 (no effort) to 10 (maximum demand) points.

Results: Quality of chest compressions was good and similar in both conditions (T21 vs T14). However, the percentage of ventilations with adequate tidal volume was lower in altitude than at sea level conditions (35.9±25.2% vs. 54.7±23.2%, p=0.035). The subjective perception of effort was significantly higher at simulated altitude (5±2) than at sea level (3±2) (p=0.038). Maximum heart rate during the tests was similar in both conditions; however, mean oxygen saturation was significantly lower in altitude conditions (90.5±2.5% vs. 99.3±0.5%, p<0.001).

Conclusion: Although performing CPR under simulated hypoxic altitude conditions significantly increases the physiological demands and subjective feeling of tiredness compared to sea level CPR, trained rescuers are able to deliver good Q-CPR in such conditions, at least in the first 10 minutes of resuscitation.

Keywords: High altitude; chest compressions; heart rate; oxygenation; CPR quality; physiology.

1. INTRODUCTION

People's interest in open air high altitude activities such as hiking, mountaineering or skiing has greatly increased in recent years [1]. Being and moving at a high altitude produces several physiological changes [2] that include an increase of cardiac and respiratory workload especially during exercise [3].

Hypoxia is the direct and most significant consequence of breathing hypoxic air (inspiratory fraction of oxygen at 3.250-meter-high is 0.14) and it's the main driver of the harmful clinical effects that occur in altitude. Above 3000m high the oxygen saturation at rest is around 90% and decreases as altitude increases [4,5]. Also, from 3000m high physiological changes become more relevant because the physiological compensatory mechanisms are not able to counteract the effect of decreased oxygen saturation. There are also other multiple factors such as low temperature, dehydration, solar radiation and low humidity, which can also affect people's health and become more noticeable with increasing altitude [6].

Apart from the greater number of people who perform mountain activities above 3000m, more than 40 million people worldwide live above this altitude. At least theoretically, anyone who is at high altitudes has increased cardiovascular and metabolic risk factors for cardiac arrest [7]. It has been reported that cardiac arrest is the second most common cause of death in the mountains [5].

After a systematic literature review, Chalkias et al [2] established recommendations for cardiopulmonary resuscitation (CPR) at high altitude. Nevertheless, the CPR at altitude European Resuscitation Council (ERC) [7] and American Heart Association (AHA) [8] guidelines are not different from to standard CPR (at sea level). It is recognized that survival and neurological outcome after cardiac arrest depend on early and quality CPR [7,9]. Then, it seems reasonable to assume that if the resuscitation environmental conditions change in terms of altitude, the quality of resuscitation as well as the rescuer's physiological demands should be affected.

Moreover, quality CPR (Q-CPR) requires a physical effort that causes fatigue even in trained rescuers; such demand may increase significantly over time in prolonged resuscitations. Consequently, it is recommended to alternate compressions and ventilations every 2 minutes or at any time when the provider feels that Q-CPR decays [7].

Prolonged CPR at high altitude might imply an important physical challenge to rescuers. Preliminary previous studies have shown that 5 minutes of CPR at altitude increased the descent of arterial blood oxygen saturation (SpO_2) and increased heart rate (HR) and subjective perception of exertion (Borg scale score) [10-12]. This fact could negatively affect the frequency and depth of chest compressions [10] and also decrease the number of effective compressions [3,10]. However, no studies have been found that analyse the quality of ventilation in high altitude conditions. Therefore, the aim of this study was to analyse the effect of oxygen fraction reduction (O_2 14%, equivalent to 3250m) on the quality of CPR (including compressions and ventilations) as well as the rescuers' physiological demands of such CPR.

2. MATERIALS AND METHODS

A quasi-experimental crossover study design was used, in a simulation laboratory.

2.1. Sample

Ten Q-CPR proficient healthcare professionals (3 women and 7 men) were invited to participate. Everyone was 18 years of age or older, they had no disease or physical handicap and all of them were up to date in CPR according to the latest recommendations ERCGR2015 [7]. One participant was excluded from the study due to technical failures of the finger pulse oximeter used in the test. Sample anthropometric and demographic variables were: age 37.4±13.0 years, height 173.6±8.7 cm, weight 77.2±17.6 kg, and body mass index 25.4±4.0 in $kg \cdot cm^{-2}$.

All participants provided written informed consent. This study respected the ethical principles of the Helsinki Convention and the Ethical Committee of the School of Education and Sport Science (University of Vigo, Spain) approved the study protocol code 02-0719.

2.2. Study protocol

Participants in teams of 2 rescuers performed 10 minutes of CPR (with a 30:2 ratio of compressions/ventilations) on a manikin with Q-CPR measurement device, alternating compressing/ventilating roles between rescuers every 2 minutes in two different situations (Fig. 2):

a) Test T21: At sea level (FiO_2 of 21%).
b) Test T14: Normobaric simulation of 3250m above sea level (FiO_2 of 14%).

Although participants performed the test in pairs, we only analysed the quality of CPR and physiological demands of the rescuer who was under the described conditions, disaggregating the data of the other partner. They performed 5 cycles of CPR for 10 minutes: cycle 1: compressions (2 min.), cycle 2: ventilations (2 min.), cycle 3: compressions (2 min.), cycle 4: ventilations (2 min.) and cycle 5: compressions (2 min.). Therefore, the cycles 1,3 and 5 were compression cycles and 2 and 4 ventilation cycles (Fig.1).

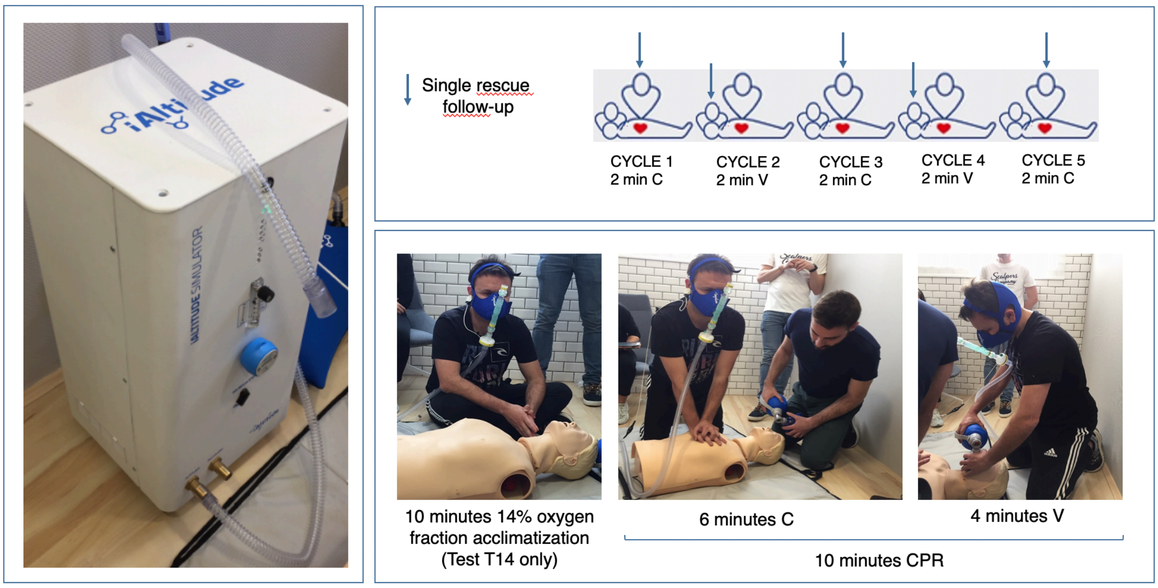

Fig. 1. CPR protocol scheme.

Abbreviations: C: compression; V: ventilation; CPR: Cardiopulmonary resuscitation.

Heart rate (HR), blood oxygen saturation (SpO_2) and modified Borg score [13] were measured or recorded during the 10 minutes of CPR of each test. Besides, in T14 test each participant had an acclimating phase to the 14% oxygen fraction for 10 minutes before to the CPR test. During that time, physiological parameters were also measured.

The order of the test was randomized. To minimize the effect of fatigue between tests each participant was able to rest for at least 40 minutes.

2.3. Materials

Altitude

The simulation of 3250m above sea level was carried out with the iAltitud Simulator® device (Madrid, Spain), that includes a hypoxia-inducing closed circuit and adjustable facial mask. Inspiratory oxygen fraction was adjusted at 0.14.

Cardiopulmonary resuscitation

Quality of cardiopulmonary resuscitation performance was analysed with a Laerdal ResusciAnne manikin with Laerdal Wireless SkillReporter (Laerdal Medical, Stavanger, Norway) configured under the recommendations of ERCGR2015 [7]. The ventilations were administered using the Bag Valve Mask Ambu® Mark IV adult.

Physiological parameters

The physiological demands of rescuers during tests were recorded with the iAltitude Trainer® software (Madrid, Spain). Heart rate and blood oxygen saturation were measured with a Pulse Oximeter (Oximeter DF8 W/USB 3018L XPOD, Ear clip SNRS 8000Q2; Nonin Medical, Plymouth, USA) located in the earlobe of each participant. In addition, each subject carried a Polar Team H7 heart rate sensor, (Kempele, Finland) in the centre of the chest.

Subjective perception of effort (modified Borg scale)

The subjective perception of exertion was recorded before and immediately after the tests according to the modified Borg scale score (ranging from 0-no exertion to 10 points-maximum exertion) [13].

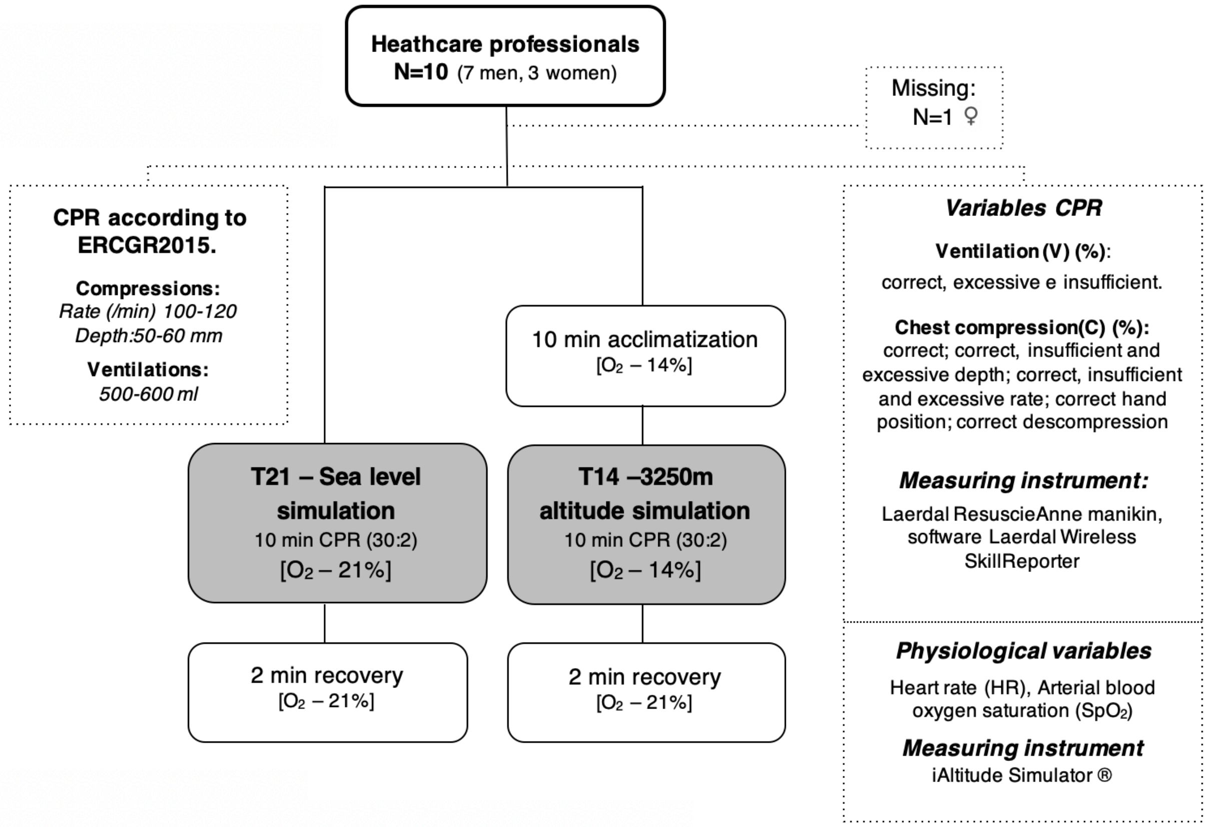

Fig. 2. Flow chart of the study design

2.4. Variables:

2.4.1. Physiological variables

The heart rate and arterial blood oxygen saturation were continuously measured during the tests and in the 10 minutes of altitude acclimatization. To calculate the maximum heart rate we used the formula of Karvonen, Kentala, and Mustala (14): HRmax = 220 – age for men and HRmax = 226 – age for women. Finally, the subjective perception of exertion was measured with the Borg scale score [13].

2.4.2. CPR variables

Variables referring to the quality of cardiopulmonary resuscitation were recorded in both tests. Target compression depth (between 5 to 6 cm), rate (between 100 to 120 per minute), full chest decompression and correct chest hands position were taken into account to evaluate chest compression quality. The evaluation of ventilation was made according to the manikin lung tidal volume (being in target range between 500 to 600 ml). The Laerdal ResusciAnne manikin was configured according to the 2015 European Resuscitation Guidelines for Resuscitation [7].

2.5. Statistical analysis

The results were analysed with the statistical software SPSS for Mac (version 25). The Shapiro-Wilk test was used to determine the normality of the sample. The variables of age, weight and height were described using measures of central tendency (mean) and dispersion (standard deviation). To analyse the CPR and physiological variables we used the repeated measures ANOVA test with two within-subjects factors: oxygen (21 vs 14%) and cycles (1, 3 and 5 to compressions / 2 and 4 to ventilations). A significance level of $p<0.05$ vas considered for all analyses.

3. RESULTS

3.1. Demographic data

From the initial 10 participants, one of them had to be excluded because of pulse oximeter failure during the test. The final study sample (n=9) consisted of 2 (22.2%) women and 7 men (77.8%).

3.2. Cardiopulmonary resuscitation quality

The results of the quality of ventilation in CPR disaggregated by cycles (2 and 4 ventilation cycles) are shown in table 1. The participants delivered more ventilations with insufficient or excessive tidal volume (that means out of target) in altitude simulation (T14) than in sea level CPR test (T21). Overall, the percentage of ventilations with adequate (on target) tidal volume was 54.7±23.2% in T21 vs. 35.9±25.2% in T14 ($p=0.035$). No significant statistic differences were found in any of the tests between the second and forth cycle of ventilation.

Table 1.
Ventilation variables in T21 (O_2 - 21%) vs. T14 (O_2 - 14%) in the two analyzed ventilation cycles (2nd and 4th).

		Cycle			*p* cycles	
		Overall (2+4)	2	4		
%Ventilation with adequate tidal volume	T21	54.7 (23.2)	58.8 (24.6)	50.6 (28.8)	0.385	0.169
	T14	35.9 (25.2)	41.5 (33.9)	30.4 (28.4)	0.397	
	p test	0.035	0.184	0.1		
%Ventilation with insufficient tidal volume	T21	18.1 (12.9)	20.9 (20.9)	19.8 (17.9)	0.985	0.851
	T14	19.3 (15.9)	20.5 (24.7)	24.3 (27.4)	0.517	
	p test	0.815	0.538	0.632		
%Ventilation with excessive tidal volume	T21	24.9 (23.4)	20.3 (28.3)	29.6 (30.3)	0.452	0.170
	T14	41.7 (37.3)	38.0 (35.6)	45.3 (43.1)	0.431	
	p test	0.073	0.171	0.230		

Level of significance: p<0.05 (repeated measures ANOVA test)

In terms of chest compressions, the results were analyzed disaggregated by cycles (1, 3 and 5 compression cycles). There were no significant differences in any of the variables analyzed when T21 and T14 tests were compared or between 3 cycles (supplementary material). The percentage of correct compressions was similar in both tests (68.9±17.4% in T21 vs. 64.2±17.0 in T14, p=0.554).

3.3. Physiological demands

The physiological demands of CPR to the rescuers' are shown in table 2. Regarding heart rate (HR), it was observed that the percentage of maximum HR is higher in cycles 1, 3 and 5 (chest compression periods) compared to cycles 2 and 4 (ventilation periods) (p=0.002) in both tests (Fig. 3). No statistically significant differences in HR were found between T21 vs. T14.

The mean arterial blood oxygen saturation (SpO_2) remained constant, with minimal variations, during the 5 cycles of CPR (10 minutes) in T21 and T14 (Table 2). However, there were significant differences between both tests; the average SpO_2 was 99.3±0.5% in T21 and 90.5±2.5% in T14 (p<0.001). As it was mandated by protocol, the fraction of inspired oxygen (FiO_2) was lower in the 3250m altitude simulation (T14) (FiO_2 = 14% in T14 vs. FiO_2 = 21% in T21).

The subjective perception of exertion was significantly higher in T14 (5±2 points) than in T21 (3±2 points) (p=0.038).

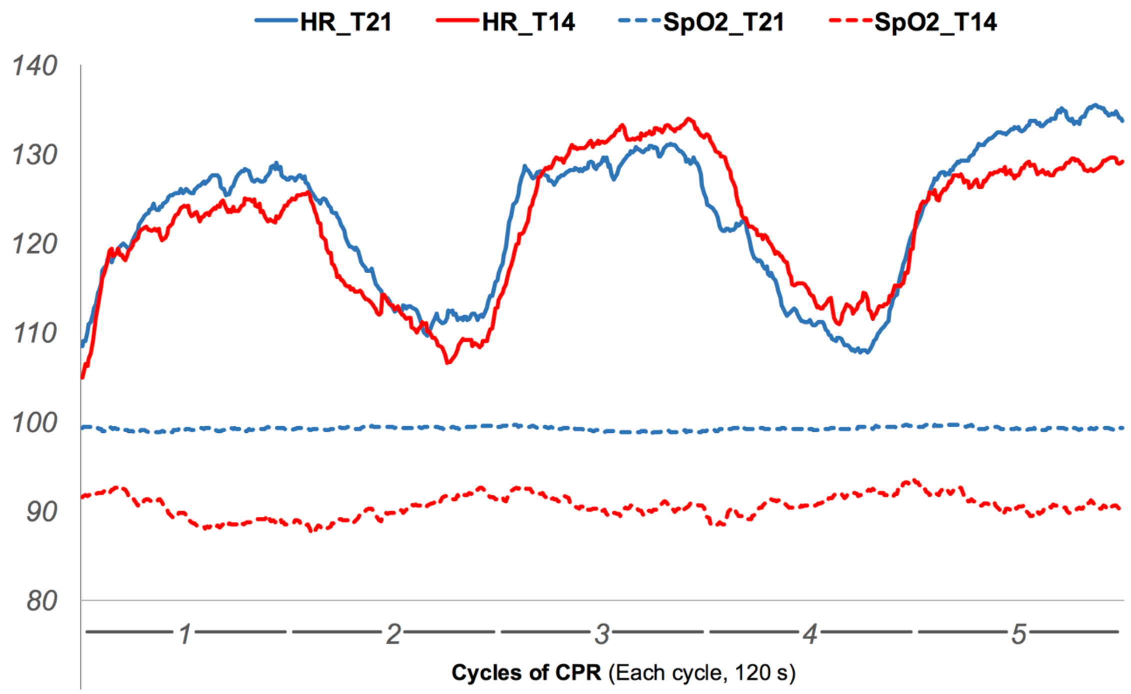

Fig. 3. Mean of heart rate (HR) and arterial blood oxygen saturation (SpO_2) of all participants during the 10 minutes of CPR.

The X-axis shows the 5 cycles of CPR (compressions: cycles 1, 3 & 5; ventilations: cycles 2 & 4) and Y-axis the values of HR and SpO_2

Table 2.
Participants' physiological demands during CPR cycles in T21 (O_2 - 21%) vs. T14 (O_2 - 14%). [1,3 and 5 compression cycles / 2 and 4 ventilation cycles].

		Cycle					*p* cycles
		1	2	3	4	5	
% of maximum HR	T21	67.4 (7.4)	63.1 (6.8)	70.0 (9.0)	62.0(8.4)	71.6 (9.0)	0.002*
	T14	65.9 (9.1)	61.7 (6.7)	70.7 (9.1)	63.7 (8.0)	69.6 (10.8)	
	p test	0.830					
Mean SpO_2	T21	99.2 (0.7)	99.4 (0.5)	99.1 (0.7)	99.3 (0.5)	99.4 (0.6)	0.159
	T14	90.0 (2.9)	90.2 (2.5)	90.7 (2.5)	90.9 (2.4)	90.9 (2.7)	
	p test	<0.001**					

Level of significance $p<0.05$ (repeated measures ANOVA test)

*Significant statistic differences between cycles (Bonferroni test) 1 vs. 5 (p=0.004), 2 vs. 3 (p=0.005), 2 vs. 5 (p=0.001), 3 vs. 4 (p=0.006), 4 vs 5 (p=0.017)

**Significant statistic differences in comparison by pairs between each test per cycle (Bonferroni test): p<0,001 in all cases.

HR: heart rate; SpO_2: Arterial blood oxygen saturation.

4. DISCUSSION

The improvement of skills for resuscitating in special circumstances is a goal and a challenge for rescue teams. One of these environmental conditions is the high altitude scenario. Our study has analyzed how the reduction of oxygen fraction from 21 to 14% in laboratory altitude conditions could affect the quality of CPR and influence the physiological demands of proficient rescuers.

CPR is considered a demanding physical exercise that quickly produces fatigue in the rescuer. This fatigue increases over time and has a negative influence on the quality of chest compressions and ventilations [15-19] and consequently compression/ventilation shifts between rescuers every 2 minutes are recommended [7,8]. We have hypothesized that CPR at altitude conditions would increase the rescuers' physical demands and their fatigue feeling.

In our study the only significant change in performance during altitude conditions CPR was a decrease in the percentage of ventilations within range of recommended tidal volume. Considering that bag-valve mask ventilation is a technical and not physically demanding task, we may speculate that hypoxemia could impair someway rescuers' fine motor skills. Previous research has reported that cognitive functions deteriorate after exposure to hypoxic conditions at high altitude [1,20-24]. In our tests, excessive volume ventilations (that would lead to hyperventilation in eventual real cases) were more frequent than insufficient ventilations (that would lead to hypoventilation). Either way, both situations would worsen resuscitation outcomes as it has been reported in previous experimental and clinical studies [25-28].

On the other hand, when chest compressions quality variables were analyzed, our participants were able to perform the skills with similar quality while breathing hypoxic and normoxic air (a non-significant variability of 3-15%

between tests was observed). While they achieved good CPR performance, rescuers felt that more effort (rated as hard) was required at altitude that at sea level conditions (rated as moderate). Similar results were observed in comparable studies [10-12,29].

Previous research has shown that heart rate increases at altitude both at rest and during physical exercise [3,10,11]. In contrast, in our tests the heart rate barely increased in 3250m altitude simulation over the baseline obtained at sea level simulation. This may be related to the fact that previous studies were done in real climb conditions and therefore the altitude conditions exposure time was longer. In contrast, Sato et al [12] in a study where a hypobaric chamber was used to create a hypoxic environment and subjects spent 1 hour in altitude conditions, observed higher HR inside the hypobaric chamber, as compared to outside, just before and after CPR but not during the chest compressions period.

As it was expected, we observed that HR significantly increased during compression cycles in comparison with ventilation cycles, that could be considered as active rest periods. But this fact happens similarly in both scenarios (T14 and T21) (Fig. 3). A longer test time in altitude simulation or a real ascent could produce changes in this variable.

When placed in hypoxic conditions the rescuers suffered from a significant SpO_2 decrease, with a mean value of 90%. However, SpO_2 practically did not change during compression (hard effort) and ventilation (no effort) cycles (Fig. 3). This coincides with previous studies: Narahara et al. [11] found that SpO_2 was significantly lower after ascending to 2700m (average SpO_2 = 88±4%) and 3700m (average SpO_2 = 80±7%) compared to sea level (average SpO2 = 98±1%). Similar results were obtained by Wang et al. [10], who observed that the SpO_2 fell significantly from 98.6±1% at sea level to 88.5±3% after rising to 3100m. In both studies, these values were practically the same after performing CPR for 5 minutes in those conditions.

Rescues at high altitude conditions have to be considered as physically demanding for rescuers. Therefore, when engaged in rescue activities, they have to take into account the involved factors like the reduction of air oxygen content, low temperature, difficulties to access to hospitals and to transport of victims and the rescue resource limitations. In some conditions, rescuers should consider the use oxygen delivery devices as well as mechanical compression devices to reduce their effort and fatigue and maintain Q-CPR along the time [2,3,6,10,11]. In addition, CPR with chest compressions and ventilation would permit some time to rest during the ventilation cycles [12].

4.1. Practical implications of this study

Our results can help healthcare and other rescue professionals to understand what physiological effect awaits them in the high altitude and to be prepared. Maintaining the same Q-CPR levels at high altitude will require more effort than usual, especially during chest compressions, but they will be aware of the potentially deleterious effects of hypoxia on the motor skills needed to perform effective bag-mask ventilations.

4.2 Limitations.

This research has been carried out in a laboratory study with a reduced sample. In addition, we have simulated a scenario of cardiac arrest with manikin that implies two weaknesses: the manikin doesn't exactly reflect the characteristics of a real victim and the rescuer may have different attitudes compared to a real case.

On the other hand, we simulated the fraction of inspired oxygen (FiO_2) at 3250m of altitude but did not take into account other conditions as humidity, solar radiation or temperature, which could have significant influence on the results. Also, participants spent only 20 minutes under hypoxic conditions and they wore a hypoxia-inducing mask that by design might interfere with CPR performance.

5. CONCLUSIONS

Trained rescuers are able to perform a good CPR under simulated hypoxic altitude conditions (FiO_2 of 14%) but at the cost of additional physiological demands and subjective feeling of tiredness. In such conditions, quality of ventilations was decreased in comparison with sea level scenario. Both facts must be anticipated by high altitude rescuers.

Acknowledge: We want to thank the healthcare and sport scientist professionals involved in the study.

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