Adaptation to the rarefied air of abysses and caves. A laboratory study

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ABSTRACT

Introduction and aims: The atmosphere in the abysses of the mountains of Garraf (Barcelona) have lower oxygen levels and higher CO_2 concentrations with respect to normality. To evaluate the risk of speleological exploration in this area, we studied 19 cavers (14 men and 5 women) while performing controlled exercise in a hypercapnic, hypoxic and normobaric atmosphere (15.2 ± 0.8% of 299 O_2 and 19,049 ± 299 ppmv of CO_2).

Methods: The study was performed in a laboratory through ergometry. Two identical tests were used: one in a standard atmosphere (NN) and another in a confined atmosphere (a hypoxic tent), with rarefied air (HH). The following parameters were monitored: electrocardiogram, heart rate, oxygen saturation of hemoglobin, lactate, capillary glycemia, and final blood pressure.

Results: The volunteers had distinct symptoms during the test with rarefied air: heat sensation (100%), dizziness (47%), headache (3%), ocular pruritus (21%), hand tremor (16%), extrasystoles (16.5%), hypertonic blood pressure behavior (26%), tachycardia (158.5 ± 15.9 bpm in rarefied air versus 148.7 ± 15.7 bpm in normal air; p<0.0002).
All participants showed reduced oxygen saturation (93.4 ± 3.4% in rarefied air versus 97.7 ± 9.92% in normal air; p<0.00004).

Discussion: Wide individual variability was found in symptoms and the parameters studied. In view of the results of this study, we recommend that a threshold of 45,000 ppmv of CO_2 not be exceeded in speleological exploration. Likewise, fitness assessment should be performed in individuals planning to enter confined atmospheres, such as the caves and abysses of this mountain.

KEY WORDS: Exogenous hypercapnia. Hypoxia. Caving. Spelunking. Potholing. Extrasystoles. Hypoxic tent.

RESUMEN

Introducción y objetivos: En el macizo del Garraf (Barcelona) las simas tienen una atmósfera con disminución de oxígeno y aumento de CO_2 respecto a la normalidad. Para valorar el nivel de riesgo en la exploración de estas cavidades estudiamos a 19 espeleólogos (14 hombres y 5 mujeres) al realizar un ejercicio controlado, en una atmósfera hipercápnica, hipóxica y normobárica (15,2 ± 0,8% de O_2 y 19.049 ± 299 ppmv de CO_2).

Métodos: El estudio se realizó en laboratorio mediante ergometría. Se realizaron 2 tests, uno en atmósfera normal (NN) y otro idéntico realizado en ambiente confinado (tienda de hipoxia), con aire enrarecido (HH). Se monitorizaron los siguientes parámetros: electrocardiograma, frecuencia cardíaca, saturación de oxígeno de la hemoglobina, lactato, glucemia capilar y presión arterial final.

Resultados: Los voluntarios presentaron diferente sintomatología durante la prueba con aire enrarecido: sensación de calor (100%), mareo (47%), cefalea (3%), prurito ocular (21%), temblor en las manos (16%), extrasístoles (16,5%), respuesta hipertónica de la presión arterial (26%), taquicardia (158,5 ± 15,9 latidos/min en aire enrarecido frente a 148,7 ± 15,7 latidos/min en aire normal; p < 0,0002).
Todos presentaron una disminución de la saturación de oxígeno (93,4 ± 3,4% en aire enrarecido frente a 97,7 ± 9,92% en aire normal; p < 0,00004).

Discusión: Se observó una gran variabilidad individual en los síntomas y parámetros estudiados. En vista de los resultados, se recomienda no sobrepasar el umbral de 45.000 ppmv de CO_2 en exploración espeleológica. Asimismo es conveniente una revisión médica de aptitud antes de internarse en atmósferas confinadas, como son las cuevas y simas de dicho macizo.

PALABRAS CLAVE: Hipercapnia exógena. Hipoxia. Espeleología. Extrasístoles. Tienda de hipoxia.

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Source of resources: Secretaria General de l'Esport of the Goverment of Catalonia.

Introduction

The Garraf range is a low mountain system of 240 km^2 close to Barcelona (maximum altitude 658 m). The presence was recently reported of CO_2 in the abysses of the Garraf[1]. This increased CO_2 was attributed to a sum of geological phenomena and calcite precipitation and gas diffusion. There is a fall in the oxygen and an increase in CO_2 in the abysses; the ratio between the increase in CO_2 and the consumption of environmental O_2 is similar in the different cavities of the range and their quotient is between 0.3 and 0.5. Other authors call this quotient cavity air index (CAI)[2] and it is different from the one found in individual observations in other parts of the planet[3-5]. In this mountain system, more than 300 abysses[6] have been discovered and explored since the late 19th century[7]. There has been no serious incident related to the phenomenon of rarefied air.

In 1979 Schaefer et al[8] began with experimental studies on chronic exposure to exogenous, normoxic and normobaric hypercapnia, in which they determined scales of symptoms in relation to the level of hypercapnia. Also in 1979, Guillerm et al[9] specified the mechanisms of the human species for adapting in a situation of exogenous hypercapnia, which allowed the admissible limits of exogenous CO_2 to be established on experimental bases depending on the time to which the subjects are exposed. These authors considered that 45,000 ppmv of CO_2 exceed the admissible threshold for humans.

Cavers develop their scientific, leisure and sports activity in caves and abysses, where they are extraordinarily isolated from the outside world.

In spring 2007, the adaptation of two groups of subjects was checked in an abyss with an atmosphere of hypoxia, displaying an infra evaluation of the symptoms of hypoxia by the subjects[1].

This research aimed at hypercapnia, was started in early 2008. The volunteers were 19 competent cavers, all familiar with the caves of the Garraf range. Their adaptation to exogenous hypercapnia was studied under conditions of normobaria and hypoxia in a confined artificial medium. The study was performed in the effort physiology laboratory in Esplugues de Llobregat (Barcelone), financied by the Government of Catalonia. Due to its nature, the study was not double blind or random. The aim of the study was to determine the symptoms the subjects displayed in an atmosphere similar to one of the abysses habitually explored in the mentioned mountain range. Specifically, a hypercapnic and hypoxic atmosphere was created under conditions of normobaria. The main objective of the study was the hypercapnia, which according to Mixon[10] is the main risk associated with the practice of potholing, and not hypoxia.

The hypothesis derived from the above study was that healthy cavers do not run a risk associated with rarefied atmospheres in the majority of the abysses of the Garraf.

Methods and material

This study was participated in by 19 cavers, all licensed and familiar with the underground atmosphere of the Garraf range near Barcelona and with potholing experience of between 2 and 42 years. The characteristics of the volunteers are described in table I.

All of the volunteers gave their informed consent. The study was submitted to the approval of the “Comité d’ètica d’investigacions clíniques de l’administració esportiva de Catalunya”. A previous medical check was made to evaluate their suitability for the exercise. Personal backgrounds of interest in 8 of the 19 subjects: asthma 2 cases, pneumonia 3 cases, arterial hypertension (HTA) 3 cases (two under treatment), pulmonary tuberculosis 2 cases, arrhythmia at rest 2 cases in the form of extra systoles detected in prior checks (an ultrasound study was made to discard associated pathologies), emphysema 1 case. Family backgrounds of interest in 14 of the 19 individuals: HTA 9 cases, coronariopathies and acute infarct of myocardium 7 cases, asthma in 1 case and emphysema in 1 case. Toxic habits in 8 volunteers: smoking 4 cases, restrained alcohol consumption 4 cases, cannabis derivatives 1 case.

A crossed study was made. The volunteers performed 2 effort tests (Ergocycle Monark model 828. GIH Stokolm) in normal air and rarefied air (inside and outside the tent, respectively) according to a rectangular load design and an intensity equivalent to 75% of the maximum theoretical heart frequency. This load was previously determined under normal atmospheric conditions. Both tests were performed in the same room, at a temperature of 22 degrees centigrade (Thermo-hygrometer MT model 503). Inside the tent, the atmosphere was saturated with a humidity of 100%, whereas outside, the atmosphere was 76%. During the ergometric tests, the cardio-

Table I Profile of the volunteers subject to study

	Age	Weight	Height	MCI	Sex
Average	36,9	70,4	168,9	24,6	14 men
Standard deviation	11,1	12,5	10,7	2,9	5 women

graphic trace was constantly monitored (model EBA 101A. Osatu.s.coop ltda.48240 Berriz. Spain), cardiac frequency was checked by pulsometer (S810i Polar Electro. Finland), haemoglobin oxygen saturation by pulsioximetry (TuffSat. Datex-Ohmeda. Louisville, USA), arterial pressure at the end of the ergometric test (Omron M7 intellisenser by Omron Healthcare. Kyoto, Japan), lactic acid (Lactate Pro. ARKRAY, Inc. Kyoto, Japan) and glycaemia (GlucocardGmeter. ARKRAY, Inc. Kyoto, Japan) from capillarised arterial blood from the ear lobe 3 minutes after the end of the ergo metric test. The volunteers were questioned about their symptoms and sensations after both tests. The questioning was open, without survey or suggestion. Four subjects did the test first in rarefied air and 15 the other way round (fig. 1).

Confined atmosphere

A confined atmosphere similar to an abyss was prepared. The hypoxia was generated by the Alpine Air device from GO_2 Altitude (Auckland, New Zealand, © Hi Pro Health Ltd, March, 1999) in a 5,000 l tent. The analysis systems of the atmosphere in a confined space were doubled (Multiple Gas detector: MultiRAE-IR. Rae systems Inc. San Jose, USA). A relative humidity of 100% was generated, the temperature was 22° Celsius, similar to that inside cavers' clothes and the hypercapnia was generated with bottled CO_2 (Abelló Linde SA). Two or three doctors were present in all the tests with suitable means for attending any medical emergency.

Statistical study

In the case of the symptoms, they were classified and listed and the percentage incidence was determined. In different cases, a regression analysis was made of matching data. Using the test we proceeded to reject or not reject the H_0 from the data achieved between the two compared situations, determining the degree of significance of the differences. The averages and standard deviations were determined of the different parameters between the two experimentation situations, and the differences were quantified. The data was treated with the Microsoft EXCEL programme.

Source of resources

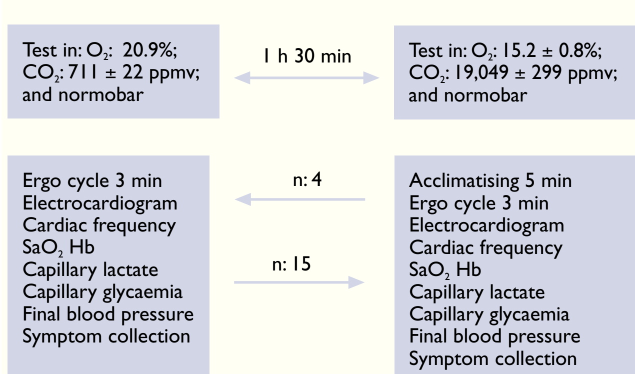
Installations, apparatus and economic resources provided by the Secretary General for Sport of the Government of Catalonia. Volunteers: they received no economic compensation for travel expenses. Origin: Spain and Andorra.

Results

The volunteers displayed symptoms when they exercised in rarefied air: sensation of heat (100%), dizziness (47%), headache (36,8%), ocular pruritus (21%), trembling hands (16%); 16% displayed a considerable increase in cardiac extrasystoles in comparison with rest or compared with the test in normal air, and 126% showed hypertonic behaviour of the systolic arterial pressure when we compare the behaviour at the end of the respective effort tests (table II).

The subjects displayed an average fall of 4.3 ± 3.38 points in the SaO_2 when they did the test in rarefied air in comparison with the test done in normal air, with extreme values of 85% and 97%. Twelve subjects showed values of under 95% SaO_2 and two below 90%. The values of the two experimentation situations displayed statistically significant differences ($p < 0.0004$) (fig. 2).

Figure 1 Experimental design.



DEFINITIONS

Exogenous hypercapnia: hypercapnia generated by an excess of CO_2 brought in from outside the body.
Isolated-peripheral medium: a medium in an extreme degree of isolation found in special situations (spacecraft, submarines, etc.) and also in potholing.
Rarified air: air that contains high concentrations of CO_2 and/or low oxygen levels, without being toxic.
CAI: quotient between the increase in CO_2 with respect to normality, divided by the fall in oxygen with respect to atmospheric normality ($CAI = \delta\ CO_2 / \delta\ O_2$).

Table II Symptoms presented in exercice in the rarified air

Symptoms	Percentage	n
Headache	36,8	7
Trembling hands	15,8	3
Disorientation	5,3	1
Heat	100,0	19
Dyspnea	26,3	5
Dizziness	47,4	9
Fall in consciousness	5,3	1
Itching eyes	21,1	4
Migraine	5,3	1
Sensation of ammonia	5,3	1
Choking	5,3	1
Hyperventilation	10,5	2
Anxiety attack	5,3	1
Cardiac and vascular alterations		
Extrasystoles	15,8	3
Systolic hypertonic reply	26,3	5

This effort made in rarefied air by our volunteers required an increase in heart beat of 10 beats a minute on average, compared with the same effort made in normal air (148.7 ± 17.7 bpm in normal air against 158.5 ± 19.9 bpm in rarefied air; $p < 0.0002$)

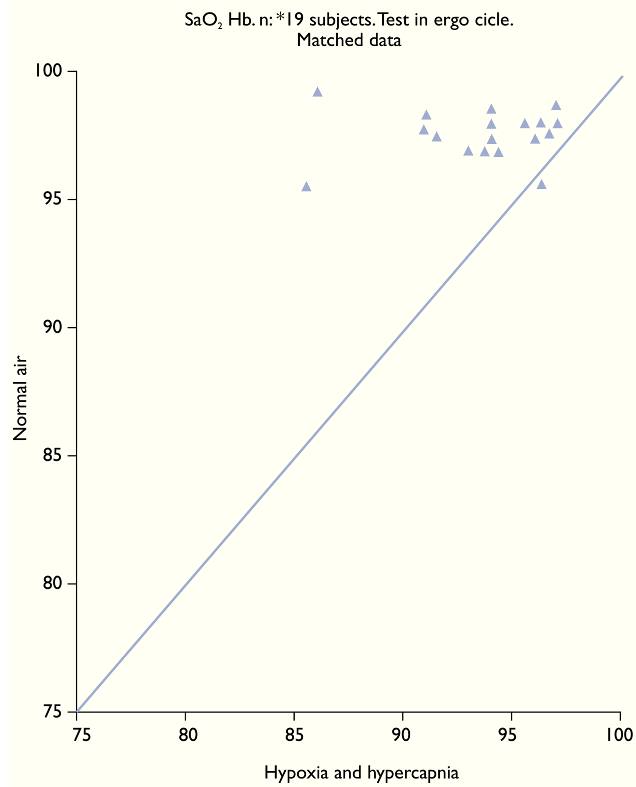
Glucaemia

The subjects gave average values of 85.5 ± 13.57 mg/dl when they did the test in normal air and 90.57 ± 14.1 9 mg/dl in rarefied air, without statistical significance, so the nil hypothesis could not be discarded (H_0).

Lactic acid

The subjects gave average values of 4.22 ± 1.39 mmol/l when they did the test in normal air and 3.58 ± 1.45 mmol/l in rarefied air, without statistical significance ($p < 0.079$), so the nil hypothesis could not be discarded.

Figure 2 The volunteers' different reactions when they did the ergo metric test in rarefied air. Two subjects displayed SaO_2 values clearly lower than 90% and 9 subjects under 95%. Seven subjects did not appear to be greatly affected by the rarefied air when measured by SaO_2. The units are expressed in %.



*One subject suffered an anxiety attack and was not able to take the test.

Systolic arterial pressure

As shown in figure 3, at least 5 of the subjects displayed hypertonic adaptation under conditions of "rarefied air" in comparison with the test performed under conditions of normal air, although the results with simple comparison of averages are not statistically significant.

Discussion

The workload to which the subjects were exposed was lighter than the load involved in climbing the rope from a well in normal potholing, as studied by Balcells et al[11] in 1986.

In contrast to the posed hypothesis, the volunteers displayed more symptoms than expected when they did the ergo metric test in a state of hypoxia-hypercapnia (HH). This also contrasts with the studies made previously in real abysses of the

Figure 3 The volunteers' replies were different in relation to the systolic arterial tension at the end of the ergo metric test; 26% had a hypertonic reaction, as opposed to the others who had a hypotonic or normotonic reply, if we compare this test with the one performed in an atmosphere of normal air. The differences were not statistically significant. The units are expressed in mmHg.

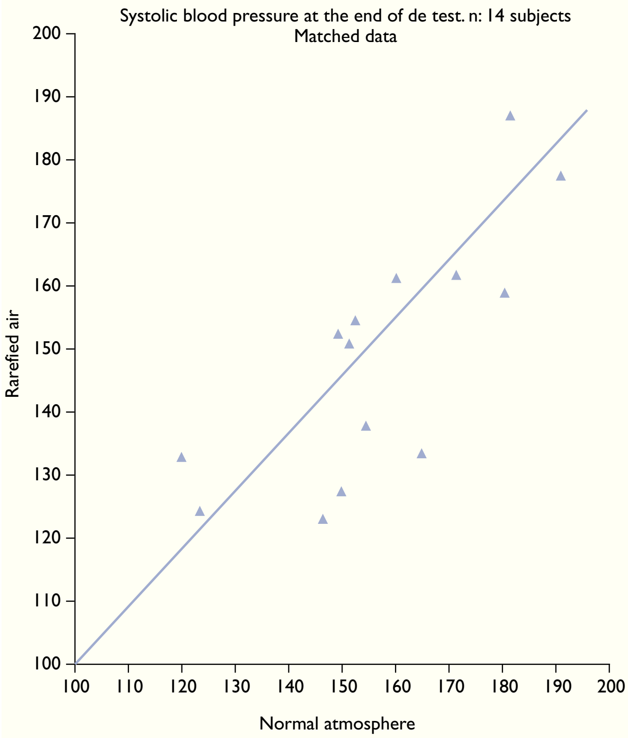


Figure 4 A volunteer subject to study in the hypoxia tent, assisted by researchers.

said mountain range, where the cavers showed infra evaluation of the symptoms of hypoxia (personal report in the process of publishing). The symptoms they displayed were different in each subject, and the number of symptoms and their intensity varied a great deal. There are subjects who behaved in HH as if there was 0.5% of CO_2, while there were others who reacted as if there was 4 or 5% CO_2 as shown by the fact that one subject had an anxiety attack and two were dizzy at the end of the test in adverse atmospheric conditions, if we compare it with the symptoms described by Radziszewski et al[12].

The results showed greater sensitivity among the subjects with early appearance of symptoms. To evaluate this, it is necessary to consider the added factors of hypoxia and the physical exercise undertaken, which behaved as aggravating elements.

The difference in relative humidity between the tent (HH) and the exterior may also have intervened as a cause of the sensation of heat and suffocation. The heart rate behaved in line with the observations of Sechzer et al[13] although with significant individual variability, displaying a tendency to increase with the same load when the subjects did the test in a rarefied atmosphere. In previous studies in an abyss in the Garraf, with rarefied air we already saw identical behaviour, as expected (personal observations in the process of being published).

The SaO_2 in the haemoglobin showed an important difference between the subjects submitted to similar conditions of oxygen restriction, so there were subjects who clearly presented SaO_2 insufficiency when doing the exercise in rarefied air. This is not surprising because the different adaptation of subjects to a lack of oxygen at high attitude in mountains is clearly established. This coincides with the observations of James & Dyson[14] which talk about *pink puffers* and *blue bloaters* to describe the different adaptation of cavers to rarefied air (0.5% CO_2 and 18% O_2 in their studies). These authors warn of the different risks facing cavers depending on their adaptation, for the subjects who do not react with hyperventilation run the risk of blacking out without warning when they are subject to rarefied air, a hazard already described by Bounhoure et al[15]. Seven of the 19 volunteers displayed respiratory symptoms compatible with the *pink puffer* model.

Conclusions

The appearance of symptoms and discomfort in our volunteers subject to an atmosphere of rarefied air was subject to considerable variability. In the same way, the adaptation of SaO_2

and heart rate also suffered considerable individual variation.

Seeing the behaviour of our volunteers, we accept the recommendation of Radziszewski et al[12] of not exceeding the threshold of 45,000 ppmv CO_2 in any case, and from our own observations we would recommend great care in atmospheres of over 30,000 ppmv CO_2 in abysses, because the accompanying hypoxia could exacerbate the effects of hypercapnia.

Recommendations for cavers

– In the abysses of the Garraf range in which the habitual composition of the atmosphere is unknown, the use of rarefied air detection procedures is recommended.

– You must leave the cavity when the first symptoms appear of poor adaptation to the rarefied air.

– Cavers are recommended to have a medical check made of their aptitude, in order to detect cardiac and respiratory problems, which make physical activity little recommendable in a confined, isolated-peripheral medium where the air is rarefied.

– In each exploration to evaluation of the suitability of the use of popular acetylene lighting, depending on the expected environmental characteristics, is recommended.

Acknowledgements

To Raúl Cano, the geologist who supervised the concepts of his speciality used in this work. To the caver volunteers who enabled this study to be undertaken.

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