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Oxygen use in Atacama large millimeter and submillimeter (ALMA) arrays in Chajnantor valley at 5050 m.

Uso de oxígeno en Atacama large millimeter and submillimeter (ALMA) en el valle de Chajnantor a 5050 m.

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ABSTRACT: The Chilean workforce has over 200,000 people that are intermittently exposed to altitudes over 4000 m. In 2012, the Ministry of Health provided a technical guide for high altitude workers that included a series of actions to mitigate the effects of hypoxia. Previous studies have shown the positive effect of oxygen enrichment at high altitudes. The Atacama Large Millimeter / submillimeter Arrays (ALMA) radiotelescope operate at 5,050 m (Array Operation Site, AOS) and is the only place in the world where Pressure Swing Adsorption (PSA) and Liquid Oxygen technologies have been installed at a large scale. Here we discuss our experience using oxygen supplementation at ALMA, to prevent the malaise and/or risks associated with exposure at 5,050 m. Antenna operators experienced chronic intermittent hypobaric hypoxia (CIHH, shiftwork 8 days HA*6 days rest SL) over 4 years. Studies to define normal O2 saturation values were performed in OSF and AOS by continuous recording during the shift. The outcomes showed no differences between production procedures (PSA or Liquid oxygen) in regulating oxygen availability at AOS facilities. As a result, big-scale installations have difficulties reaching the appropriate oxygen concentration due to leaks in high mobility areas. In addition, the PSA plant requires adequation and maintenance to operate at a very high altitude.

KEYWORDS: PSA, liquid oxygen, very high altitude, chronic intermittent hypobaric hypoxia.

INTRODUCTION

"Our ancestors were able to read the signs in the sky to survive the vagaries of climate and enjoy the bounty of Mother Earth (…) now we know that our ancestors are true observers of the heavens and the first true astronomers in Atacama" (Cruz et al., 2013: The Universe of Our Elders).

Atacama Desert is located approximately at 30° SL, enclosed by two mountain ranges: the Andes mountains to the east and the Domeyko mountain range to the west, covering 181,300 km2. This territory emerged 20 million years ago, characterized by salt basins, sand and lava flows, and dry soil. The cold Humboldt current and the Pacific anticyclone are fundamental in maintaining a dry climate, with high-temperature oscillations, making this territory ideal as a test site for NASA probes due to its similarity with Mars soil.

In 1999, the European countries, North America, and Japan formed a consortium represented by the National Radio Astronomy Observatory (NRAO), European Southern Observatory (ESO), and National Astronomical Observatory of Japan (NAOJ) to evaluate a place in the world for a new telescope. Chajnantor plateau, located 30 Km from the town of San Pedro de Atacama and the town of Toconao, was selected as the primary candidate because of its high clear fraction and very low water vapor perception (<0.5 mm): supporting all the required conditions for installing this new telescope. This was demonstrated by using the GOES-8 satellite infrared imaging data (Motohara *et al*., 2011). The origin of the word Chajnantor, means "lugar de partida" ("place of departure") in the Kunza language of the Atacameños, or Likan Antai -the original indigenous people that inhabited this place over 6,000 years BC (Mostny, 1971). The construction of

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the Atacama Large Millimeter/ submillimeter Array (ALMA) started in 2003 and was finalized in 2013 with the installation and operation of 66 antennas that is now known as ALMA on the Chajnantor plateau at 5,050 m.

ALMA has two locations: the first is located 16 kilometers from the town of San Pedro de Atacama and represents the base camp or Operations Support Facility (OSF) at 2,900 m, provides all personnel facilities (residential, food services, and leisure facilities) and the second is the Array Operation Site (AOS), where the 66 antennas are located in the Chajnantor Valley. This valley is located 40 km from OSF at an altitude of 5,050 m. The full personnel capacity of ALMA (OSF and AOS) is close to 400 people, including scientists, operation specialists, and services that operate in chronic intermittent hypobaric hypoxia exposure, exposed to shiftwork of 8 days of work at high altitude and 6 days of rest at low altitude (<1,000 m) (Moraga *et al*., 2018).

Both staff and visitors are required to withstand harsh environmental conditions such as high altitude (over 5,000 m), temperatures below -27°C, wind speeds up to 80 km/hr, and elevated thermal radiation. These environmental conditions can cause significant delays in the work schedule (i.e. cut road) compared to similar tasks at lower altitudes. Additionally, companies encounter great difficulties in selecting and retaining specialized personnel, due to the low tolerance of altitude. Similar evidence of heavy weather conditions and their effects on workers during the construction of the Qinghai-Tibet railroad in the Tibetan plateau was reported by Wu *et al*. (2007).

Effects of high altitude on the human population

The first documented account in the western hemisphere of malaise associated with high-altitude was made by a priest named José de Acosta, crossing the Andean mountain range in Perú (Pariacaca) at 4,800 m, during a Hispanic conquest in South America in 1590. He described a characteristic malaise in animals and humans due to the "thinness of the air" (see Gilbert, 1980). This wonderful description was made 58 years before it was proven that barometric pressure falls at high altitudes (See Ward *et al*., 2000).

Nowadays, we know that the fall in atmospheric pressure at high altitudes decreases the partial pressure of inspired oxygen (Table I). However, the percentage of oxygen in inspired air is constant at different altitudes. Dalton´s Law proposes that barometric pressure represents the sum of the partial pressures of the constituent gases (N2, O2, H2O vapor, CO2, Argon, others). In the airway and alveolus, the partial pressure of water vapor is near 47 mmHg, considering a corporal temperature of 37°C. If we consider that dry air has an oxygen percentage of 21%, the inspired oxygen pressure is $0.21 \times (760 - 47) = 150$ mmHg at sea level.

Table I. Inspired partial pressure of oxygen at several altitudes

	Altitude (meters)	Barometric pressure (mmHg)	Inspired PO2 (mmHg)
Antofagasta	0	760	149.2
San Pedro de Atacama	2408	576.1	110.8
OSF ALMA	2900	543.3	103.9
AOS ALMA	5050	417	77.4

Early studies by Paul Bert in 1878 assumed that the lower inspiratory pressure of oxygen is the primary stimulus for adaptation to hypoxia (See Conkin and Wessel, 2008). Afterward, Ravenhill in 1913, made a more complete description of several types of "puna" (known as acute mountain sickness, pulmonary edema, and cerebral edema), during the medical overseeing of the mine "La Poderosa" in Northern Chile (Ward *et al*., 2000), also known as "Collahuasi". Later, studies performed in hypobaric chamber showed a relationship between reduced atmospheric pressure and reduced oxygen pressure, and during the expedition organized by Barcroft to Morococha (Perú) in 1920-21, they observed that decreased oxygen affected the physiological response during acute exposure to high altitude; and, 10 years later, the expedition to Aucanquilcha-Chile, organized by Dill in 1935 demonstrated the effect of chronic exposure of miners to high altitude. Afterward, the effects on permanent residents of the Andean Plateau, known as Chronic Mountain Sickness or Monge's Disease, were published (Monge, 1948). Nowadays, we know that the incidence of acute mountain sickness depends on altitude, previous experience, the velocity of ascent, and is limited by exposure time. There are also more severe alterations such as pulmonary and cerebral edema (Davis and Hackett, 2017).

Several types of exposure to hypobaric hypoxia

This geographical condition exposes people to an environment with reduced barometric pressure, and hence reduced oxygen availability, a condition called hypoxia. Today about 140 million people live or work at altitudes at or above 2500 m (Moore 2001). According to the periodicity of exposure, hypoxia can be acute (observed in tourists, climbers, and hikers), chronic (people who live permanently at high altitudes, between 3000 and 4500 m), and intermittent (people who alternate exposure between hypoxia and normoxia) (Gassmann *et al*., 2020). However, the term "intermittent hypoxia" referrs to a wide spectrum of contexts: Episodic intermittent hypoxia (EIH), observed in obstructive sleep apnea-hypopnea syndrome (OSAHS); Intervallic intermittent hypoxia (IIH), observed during intercontinental commercial flight crews; and Chronic intermittent hypobaric hypoxia (CIHH), observed in people who work under a shift system at high altitude and rest at sea level (see Viscor *et al*., 2018).

The CIHH model of exposure is common in the mining industry in the Andes and the Central Asian regions but is also observed in astronomical observatories, and border control personnel (including military, police, and customs) in many high-elevation countries (Moraga *et al*., 2014, 2018a, 2018b, 2019). However, in Chile over 200,000 people ascend to high altitude for work (http://herramientas.ccm.cl/eflm/pdf/ReporteCCM.pdf). Nowadays, we know that this exposure model is associated with acute mountain sickness, sleep disorders, polycythemia, pulmonary hypertension, and an acute increase in arterial pressure to exposure, and are present each time workers arrive at their worksite at high altitude and do not disappear over time (Richalet *et al*., 2002, Moraga *et al*., 2014, Moraga *et al*., 2018). To meet the requirements of the work unions of mining companies and studies about the health conditions and safety of work at high altitude, the Chilean Ministry of Health recognized altitude exposure as a health risk and by Decree 28 of 2013 defined Chronic Intermittent Hypoxia exposure when workers are exposed to altitudes over 3000 m for business reasons for more than 6 months, with a minimum stay of 30% of the time in rotating work shifts at high altitude and rest at low altitude (http://bcn.cl/1vgrd). Also, Decree 28 recognized polycythemia and pulmonary hypertension as occupational diseases derived from hypobaric exposure. Considering this, in 2014, the Ministry of Health provided a technical guide for high altitude workers that includes a series of recommendations to reduce malaise or risk during exposure to altitudes over 3,000 m and considers altitudes over 5500 m as extreme altitudes (https://www.minsal.cl/sites/default/files/guia_hipobaria_altitud.pdf).

The objective of our present article is a narrative description of cumulate experience in the use of oxygen supplementation during the operation of labors in ALMA at 5,050 m.

Strategies to enhance oxygen supplementation at high altitudes

One way to avoid the consequences of high-altitude hypoxemia is an increase in ventilation to reduce the equivalent altitude (altitude which provides the same PO2 in moist inspired gas during ambient breathing). However, a second procedure to reduce the equivalent altitude proposed increasing the PO2 in the room using an artificial increase in oxygen supply (Cudaback, 1984). West explored the possibility of oxygen supplementation at high altitudes, to reduce the malaise associated with high altitude exposition, i.e. miners camp, observatories, hotel, train, schools, and hospital (West, 2016). He defined that each increase of oxygen by 1% resulted in a reduction equivalent of 300 m (West, 1995, Luks and West, 1998, West 2002). In a pilot study in ALMA located at 5050 m in a room where the oxygen concentration was enriched to 28%, we obtain a PO2 equivalent of an altitude of 2900 m, which was associated with oxygen saturation values equivalent to 2900 m (Moraga *et al*., 2018). However, the fire hazard in ambient air decreases at high altitudes compared with sea level, since the decrease in the partial pressure of oxygen reduces the number of oxygen molecules available for combustion (West, 1995).

Nowadays, it is possible to recognize two different procedures to provide supplemental oxygen in the workplace at high altitudes: First, an oxygen concentrator, a device containing a nonflammable ceramic material (zeolite) that when is pumped at high pressure separates the nitrogen, increases the oxygen concentration to 90-95% (more detail, see West 1995). In a series of reviews, oxygen concentrators were proposed as low-cost in installation and maintenance and only required the support of electrical power (West., 1995, Luks and West, 1998, West, 2002); Second, the use of liquid oxygen, that requires the installation of bigger tanks with liquid oxygen obtained by a cryogenic plant. In both cases (oxygen concentrators or liquid oxygen) is required for installing the pipeline, valves, sensors, and control system to maintain O2, CO2, temperature, and humidity (See West., 1995, 2002, Moraga *et al*., 2014, Moraga *et al*., 2018)

In 2008, ALMA installed an oxygen generator in an on-site oxygen-generating machine capable of producing oxygen through a separation process that employs a technology called Pressure Swing Adsorption (PSA). The heart of this technology is a material called Molecular Sieve, an inert, ceramic-like material (zeolite) designed to adsorb N2 more readily than O2, increasing the oxygen concentration to 90-95% (more detail, see West 1995) to satisfy the requirements of oxygenation in all AOS dependencies at 5050 m; obtaining an oxygen concentration of 28% with the equivalent oxygen of 2900 m. The molecular sieve will last indefinitely, as long as it does not become contaminated with water and oil vapors. However, after a series of operational troubles, the PSA plant was shut down in 2011. Inspection reports indicated a series of malfunctions: oil contamination along the air preparation route was unacceptable due to the risk of rapid self-ignition and possible explosions with fatal consequences for the operating staff of the ALMA project. Second, zeolite beds, O2 storage tanks, and pipelines needed to be exchanged due to the oil and water contamination mentioned in the report. Our experience was corroborated in an article that mentioned that regular maintenance is required, such as cleaning cabinet filters, changing bacterial and particulate filters and zeolite columns after 15,000-20,000 hrs of use, depending on local conditions (Litch and Bishop, 2000). The same authors indicated that output oxygen concentration at high altitudes decreases by approximately 10% for each 2000 m gain in elevation (Litch and Bishop, 2000). Therefore, we expect a decrease in oxygen concentration by 25% at 5,050 m. This suggest that the PSA plant at very high altitude it efficiency decrease. Then, how is it possible that this technology is not helpful at very high altitudes? In our opinion, the studies that supported this technology were performed at an altitude of 3,800 m and simulated 5,000 m by reducing FiO2 (Gerard *et al*., 2000). However, this study did not consider the loss in equipment efficiency at very high altitudes, as mentioned by Litch and Bishop (2000). In this sense, we believe that the installation of the PSA plant at high and very high altitudes requires that efficience of this technology are validate in real ambient condition such as: very low pressure, dust, air dry, etc. and considere the periodic maintenance.

The Indio mine at 4200m, has experience with the use of liquid oxygen (Moraga *et al*., 2014) and the Collahuasi mine has taken the same route -with 60 oxygen-enriched dormitory rooms using liquid oxygen. A pilot study was performed in 2011 with a comfortable and mobile module (OxymindTM, INDURA, Chile) in the AOS facilities at 5,050 m where liquid oxygen was administered to the room air, to increase oxygen concentrations to 28 ± 0.5%, representing an equivalent altitude of 2,900 m (for more detail, see Moraga *et al*., 2018). Also, since 2015 ALMA has incorporated the use of liquid oxygen to enrich AOS facilities at 5050 m. Table II shows ambient measurements of O2, relative humidity, and temperature at all AOS sites. We observed that major O2 variations could be observed in the corridor, hall, and dining room (in a mean 26.1±1.3 %). These variations could be explained by the fact that these areas are connected with AOS access, and despite the access having double doors, the movement of personnel results in the doors being constantly opened and closed. In contrast, offices and correlators have access through doors that are usually maintained closed. However, evaluations of oxygen saturation and heart rate performed in all subjects during ascents to AOS, showed higher arterial oxygenation and lower heart rate values (Table III), the values reported in the present study are similar to those previously described (Moraga *et al*., 2018).

Table II. Conditioning and ambient O_2 enrichment in the AOS dependence.

	O_2 enrichment dependence (%)
Corridor	25.5±1.5
Hall	26.3±1.3
Dining room	26.5±1.2
Office	27.5±0.8
Correlator	28.0±0.5
All AOS	26.8±1.1
Temperature (ºC)	18.5±1.2
Relative Humidity (%)	29.1±3.1

Mean ± SD

Table III. Cardiorespiratory variables evaluated inside the O2-enriched AOS dependence.

	Arrive at 5050 m	
	(outside AOS)	(inside AOS + O2)
Oxygen saturation (%)	82.6±2.8	89.5±1.4 *
Heart rate (bpm)	110±9.2	78.6±8.6 *

Mean±SD, * p<0.05 outside vs inside

CONCLUSION

No differences were observed between both oxygen production procedures (PSA or Liquid oxygen) in regular operations. Big-scale installations have difficulties reaching the oxygen concentration due to leaks in areas of high mobility. However, the PSA plant requires adequation and maintenance to operate at a very high altitude.

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RESUMEN: La fuerza laboral chilena cuenta con más de 200.000 personas que están expuestas intermitentemente a altitudes superiores a los 4000 m. En 2012, el Ministerio de Salud entregó una guía técnica para trabajadores de altura que incluía una serie de acciones para mitigar los efectos de la hipoxia. Estudios anteriores han demostrado el efecto positivo del enriquecimiento de oxígeno en altitudes elevadas. El radiotelescopio Atacama Large Millimeter/submillimeter Arrays (ALMA) opera a 5.050 m (Array Operation Site, AOS) y es el único lugar en el mundo donde se han instalado tecnologías de adsorción por cambio de presión (PSA) y oxígeno líquido a gran escala. Aquí discutimos nuestra experiencia usando suplementos de oxígeno en ALMA, para prevenir el malestar y/o los riesgos asociados con la exposición a 5.050 m. Los operadores de antena experimentaron hipoxia hipobárica intermitente crónica (CIHH, trabajo por turnos 8 días HA*6 días descanso SL) durante 4 años. Se realizaron estudios para definir valores normales de saturación de O2 en OSF y AOS mediante registro continuo durante el turno. Los resultados no mostraron diferencias entre los procedimientos de producción (PSA u oxígeno líquido) en la regulación de la disponibilidad de oxígeno en las instalaciones de AOS. Como resultado, las instalaciones a gran escala tienen dificultades para alcanzar la concentración de oxígeno adecuada debido a fugas en áreas de alta movilidad. Además, la planta de PSA requiere de adecuación y mantenimiento para operar a gran altura.

Keywords: PSA, oxígeno líquido, altitud muy elevada, hipoxia hipobárica intermitente crónica.

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