ALMA Memo No. 549
Reference values of arterial oxygen saturation and heart rate at the ALMA site

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Abstract

Arterial oxygen saturation (SpO_2) and heart rate at the ALMA site were monitored with portable pulse oximeters for an astronomer over five years. A set of data is presented to provide a reference range of these values at the ALMA site.

1 Introduction

Major observatories operating in submillimeter wavelength are located at dry high sites. Located at 5050 m above sea level, ALMA is among the highest observatories in the world.

High altitude can however be dangerous to health. It is primarily because barometric pressure at an altitude of 5050 m, for instance, is reduced to 536.6 hPa, which is 53% of the sea level value (Figure 1). At this elevation, the oxygen partial pressure is reduced by the same factor, resulting in reduction of arterial oxygen saturation (SpO_2), though not linearly. It is possible that the decrease in SpO_2 becomes an important key in developing acute mountain sickness (AMS), high altitude pulmonary edema (HAPE), and high altitude cerebral edema (HACE). In the case of construction and operation of telescopes like ALMA, potentially even larger risks could result from improper operation of machines and drowsy driving brought on by the decrease in cerebral oxygenation.

High-altitude medicine has been extensively studied with particular emphases on mountaineering, high-altitude mining, and high-altitude habitants. Construction and operation of ALMA, however, have several different aspects from the above cases. The first is the tolerance of the persons to high-altitude conditions. Scientists, engineers, and technicians are usually untrained for works at high altitude, and are assigned to their positions as specialists without special considerations to high-altitude work. Another point is the mode and speed of transportation to elevation. Unlike mountaineering, we very rapidly go up and down everyday by car in just an hour between the 2500 m base camp and the 5000 m site. Even those who are not acclimatized can easily reach a high-altitude site, and are often required to act as an important member of the party from the first day of the visit. Finally, the work for ALMA includes highly intellectual or cerebral ones that require a high activity of brain effort that consumes plenty of oxygen. Work also includes activities which, if performed improperly, could lead to critical accidents.

So far there are several studies on health and work at high-altitude observatories, initiated for the 4000 m-class Mauna Kea Observatories [1–3] and later extended to the even higher ALMA site [4–8].

To prevent any critical accidents, it is advisable to monitor the degree of symptoms. The degree of the symptoms depends on individuals and their health conditions, and is often difficult to be sensed by others. There are several means that indicate the degree of the symptoms or the risks. The Lake Louise AMS score is a self-reported questionnaire that is widely used. Hackett's established AMS score is a structured interview and physical examination. An alternative and more objective measure is SpO_2. Pulse oximetry has the advantages that it is non-invasive, easy to use, and gives an SpO_2 reading within seconds after application of the transducer. SpO_2 also serves as a good measure that discriminates hyperventilation from mountain sickness.

ALMA started to monitor SpO_2 and heart rate both at its Operations Support Facility (OSF) and Array Operations Site (AOS), but so far no reference data were given primarily because of personal information protection. Since monitored data without any reference data for comparison will make little sense to the subject, here we present as a reference for self-diagnosis purpose a series of SpO_2 and heart rate data collected from one volunteer who personally agreed on this research. Similar data sets have already been collected for dozens of individuals (mostly Japanese astronomers and engineers), though they will not be archived.

There are many health issues related to high-altitude workplaces other than mountain sickness, and refer to the related ALMA Memos for the effects of and preventative actions against enhanced UV and cosmic-ray radiations at the ALMA site [9, 10].

2 Measurements

Monitoring of arterial oxygen saturation (SpO_2) and heart rate was carried out with handy pulse oximeters (Minolta Pulsox M-24) worn around the wrist (Figure 2). Measurement of SpO_2 with the oximeter is based on the principles of light absorption and transmission in oxygenated and deoxygenated hemoglobin in vessels. Lights of red and infrared wavelengths (665 and 880 nm) are emitted through the subject's finger, and SpO_2 and heart rate can be determined by detecting the spectral absorption and the fluctuating signals caused by blood flow, respectively.

This instrument recorded SpO_2 and heart rate every 5 s with a start time in the data recorder that stores data up to 24 hours in its internal memory. The stored data were downloaded to a PC through the IF-M interface connected via RS-232C and using the DS-M software.

Healthy Japanese male astronomer of age 34–40 years, height 178 cm, and weight $\simeq$ 80 kg served as a subject. Informed consent was obtained before examination. The data were collected over a five year period on the same subject, whose arrival and departure dates are summarized in Table 1. The work at high-altitude was mostly field work, but was not routine. Throughout the measurements, the subject stayed at San Pedro de Atacama (2450 m a.s.l.) for asleep, and drove the car himself to/from Pampa la Bola (4800 m a.s.l.) using the Jama Pass International Highway (CH-27).

During the measurements, altitude was usually not recorded to ensure safe driving. Instead, departure/arrival times from/to the sites were recorded. Based on the records of departure/arrival time and a typical altitude profile of going up during the commuting measured once with a handheld Garmin GPS 12XL receiver by a navigator (Figure 3), time can be converted into altitude. The corresponding altitude profile on the way back from the high-altitude site may be similar, except that the profile is reversed and that the slope of the time profile is slightly steeper because of faster downhill speed than uphill.

Table 1. Log of visit to San Pedro de Atacama (1999 November – 2006 April)

Arr. date yyyy-mm-dd	Dep. date yyyy-mm-dd	Main tasks
1999-11-02	1999-11-13	Site testing (radiosonde)
2000-01-26*	2000-02-12	Site testing (geotechnical study)
2000-06-22	2000-07-04	Site testing (soil resistivity)
2000-09-09*	2000-09-17	Site testing (maintenance)
2001-03-01*	2001-03-15	Site testing (maintenance)
2001-04-25	2001-05-06	Site testing (maintenance)
2001-09-06	2001-09-10	ASAC site tour, site testing (maintenance)
2001-12-07	2001-12-13	Site testing (maintenance)
2002-01-08	2002-01-22	ASTE assembly at San Pedro de Atacama
2002-02-25	2002-03-15	ASTE assembly at San Pedro de Atacama and transportation to Pampa la Bola
2002-04-04	2002-04-10	Site testing (maintenance), ASTE public hearing at San Pedro
2002-10-25	2002-10-28	Site testing (maintenance)
2002-10-31	2002-11-02	ACC site tour
2003-01-09	2003-01-20	Site tour, site testing (maintenance)
2003-02-27	2003-03-08	Site testing (maintenance)
2003-11-04	2003-11-06	ALMA Groundbreaking Ceremony
2004-07-09*	2004-07-19	Filming, site testing (maintenance)
2004-11-01	2004-11-15	Site testing (maintenance), ALMA Board site tour
2005-01-04	2005-01-11	ASTE operation
2005-03-10*	2005-03-20	Site testing (maintenance)
2005-04-23	2005-04-26	Site testing (maintenance)
2005-06-17*	2005-06-23	ASTE operation, site testing (maintenance)
2005-07-09*	2005-07-18	ASTE operation, site testing (maintenance)
2005-09-16*	2005-09-26	ASTE operation, site testing (maintenance)
2005-10-29	2005-10-31	ALMA Board site tour
2005-11-23	2005-11-26	San Pedro de Atacama ceremony
2005-12-07	2005-12-09	Installation of i-CAN camera at OSF
2006-01-13	2006-01-15	OSF/AOS tour
2006-03-19	2006-03-22	OSF/AOS tour
2006-04-12	2006-04-15	OSF/AOS tour
2006-04-26	2006-04-29	Meeting at OSF, Chajnantor tour

Note: The visits marked with asterisks (*), for which significant amount of data are available, were analyzed in this study. Typical work intensity of each visit depended on the main tasks, and was high for geotechnical study and soil resistivity measurements, medium for the other site testing activities and ASTE operation, and low for tours and filming.

3 Results and Discussion

3.1 Human Response to High Altitude

Presented in Figures 4–11 are series of time profiles of oxygen saturation (SpO_2) and heart rate measured at the ALMA site during different period.

From these figures, it is clear that SpO_2 of the test subject is around 93% at San Pedro de Atacama (2450 m), and significantly reduces at the 4800 m site. Compared to typical sea-level values (98%), the values measured at San Pedro de Atacama already show slight but significant decrease. This 2450 m altitude is usually considered below threshold of mountain sickness, but researches indicate that there are several people who already develop symptoms of acute mountain sickness (ref.). It was confirmed in our earlier study [6], which pointed out that the person with very low SpO_2 value at the high site already showed a hint of decrease in SpO_2 at San Pedro de Atacama.

It is also evident that the SpO_2 significantly scatters in time at high altitude, reaching more than 20% peak-to-peak in short time range. For instance, on the first day of the visit, the lowest SpO_2 value usually records as low as 60% while it occasionally jumps up to $> 90\%$. This means that spot measurement of this value may intrinsically have significant scatter from the median value, resulting in misinterpretation of the global trend. The scatter of SpO_2 tends to be larger for the first few days than the later days.

We also note that, in many cases, SpO_2 becomes lower just before departure and just after arrival. This may be due to preparatory or downloading works associated to the travel.

As for the heart rate, the scatter is even larger, partly because of erroneous readings due to low perfusion. If we focus on the better quality data taken during transportation to and from the high-altitude site – when the posture of the body is more stable and relaxed, we can see increasing trend of heart rate as a function of altitude. This is naturally understood as one of the preventative actions of human body to reduced oxygen environment.

Both the changes of SpO_2 and heart rate at the high site seem gradually become less significant as time goes by. We will touch on this issue in the next subsection.

3.2 Acclimatization

It is known that continuous exposure to low-oxygen environment introduce "acclimatization" of human bodies.

Figure 12 shows median values of oxygen saturation (SpO_2) at high-altitude site as a function of days of acclimatization. The trend described in the above subsection is more clearly visible: Although there are some scatters, the median of SpO_2 significantly increases in the first few days, from around 70% to around 80%, an increase of about 10%. In the case of the present test subject, the median of SpO_2 seems to settle around 82% after one week of the stay.

Although the 2005 July visit followed the 2005 June visit with just two weeks separation, the trend observed during the 2005 July visit had no significant difference with others. This implies that the acclimatization lasts less than two weeks after descent, and that we should simply repeat the regular procedures for acclimatization.

No hint of improvement of median of SpO_2 on the first day was observed after five years of sequential exposure to high-altitude.

3.3 Recommended Actions

Based on our experiences accumulated through more than ten-years' site testing activities in Chilean Altiplano and more than four-years' operations of the Atacama Submillimeter Telescope Experiment (ASTE) telescope at Pampa la Bola, as well as the results of the present measurements, the NAOJ Safety Guideline has the following additional requirements included:

- Preparatory period — Sleep at least one night at San Pedro de Atacama (2450 m) or Calama (2300 m) or locations with comparable altitude (such as ALMA OSF at 2900 m) for acclimatization and rest, before visiting the 5000 m site.
- Work day length — Strictly limit work hours at the 5000 m site not to exceed 4 hr a day for the first day, 6 hr for the second day, 8 hr for the third day to a week after, and 10 hr afterwards. This defines strict upper limit to the work day length irrespective of selfish decision (or non-decision) of the leader of the party, easing the mental conditions of those who cannot determine their work day lengths by themselves. This also improves the overall efficiency of the work at high altitude, and will aid support team at the base camp for early detection of accidents or unusual conditions, if any.

These have so far been very successful in preventing from severe mountain sickness and accidents and were acknowledged by the members, and thus it is encouraged to include these points in the general ALMA Safety Guidelines.

4 Summary

Arterial oxygen saturation (SpO_2) and heart rate at the ALMA site were monitored with portable pulse oximeters for an astronomer over five years. A set of data is presented to provide a reference range of these values at the ALMA site.

The SpO_2 of the test subject was around 93% at San Pedro de Atacama (2450 m), and significantly reduced at the 4800 m site. Compared to typical sea-level values (98%), the values measured at San Pedro de Atacama already show slight but significant decrease. It is also evident that the SpO_2 significantly scatters in time at high altitude, reaching more than 20% peak-to-peak in short time range. This means that spot measurement of this value may intrinsically have significant scatter from the median value, resulting in misinterpretation of the global trend.

As for the heart rate, the scatter is even larger, partly because of erroneous readings due to low perfusion. Using better quality data taken during transportation to and from the high-altitude site, increasing trend of heart rate as a function of altitude was observed.

In the case of the present test subject, the median of SpO_2 significantly increased in the first few days, from around 70% to around 80%, and settled around 82% after one week of the stay. Two series of data with just two weeks separation indicate that the acclimatization lasts less than two weeks after descent, and that we should repeat the regular procedures for acclimatization.

Based on the above results and experiences accumulated through more than ten-years' site testing activities in Chilean Altiplano and more than four-years' operations of the ASTE telescope at Pampa la Bola, several recommendations to the Safety Guideline were given.

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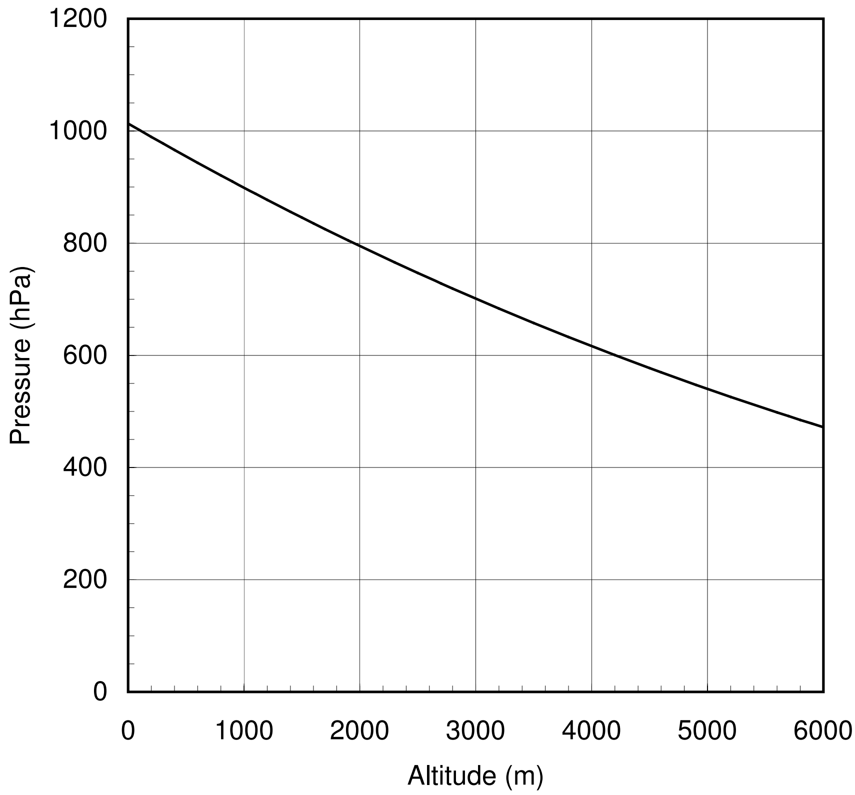

Figure 1: Height profile of barometric pressure of the ICAO Standard Atmosphere. Barometric pressures of the ICAO Standard Atmosphere at ALMA Array Operations Site (AOS; 5050 m), Pampa la Bola (4800 m), ALMA Operations Support Facility (OSF; 2900 m), and San Pedro de Atacama (2450 m) are 536.6, 554.8, 710.0, and 751.5 hPa, respectively. Height profile of the barometric pressure $p(z)$ from $z = 0$ to 6000 m is fitted by $p(z) = 1022 \exp[-z/(7855\,\mathrm{m})]$ hPa with less than 1% error (comparable to time variation).

Figure 2: Minolta Pulsox M-24 worn by the subject.

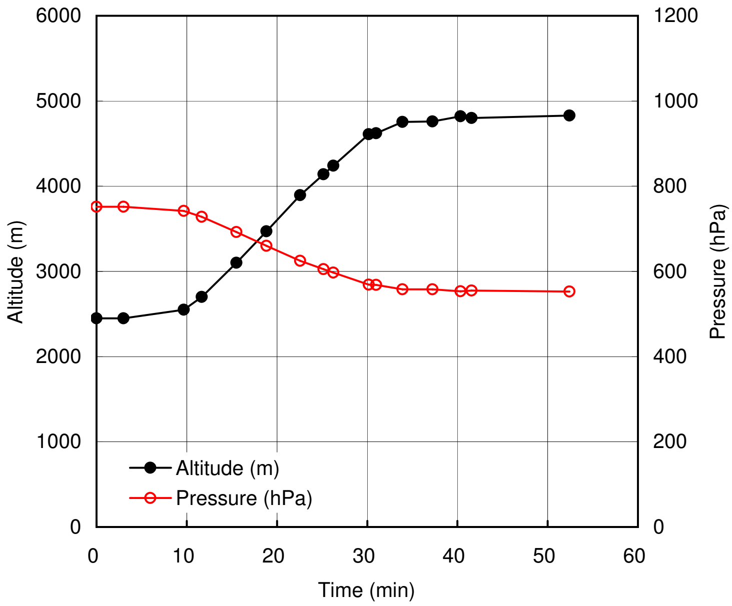

Figure 3: Typical altitude profile of a work day on the way to the high-altitude site measured with a handheld GPS, as well as corresponding barometric pressure expected from ICAO Standard Atmosphere (*red*).

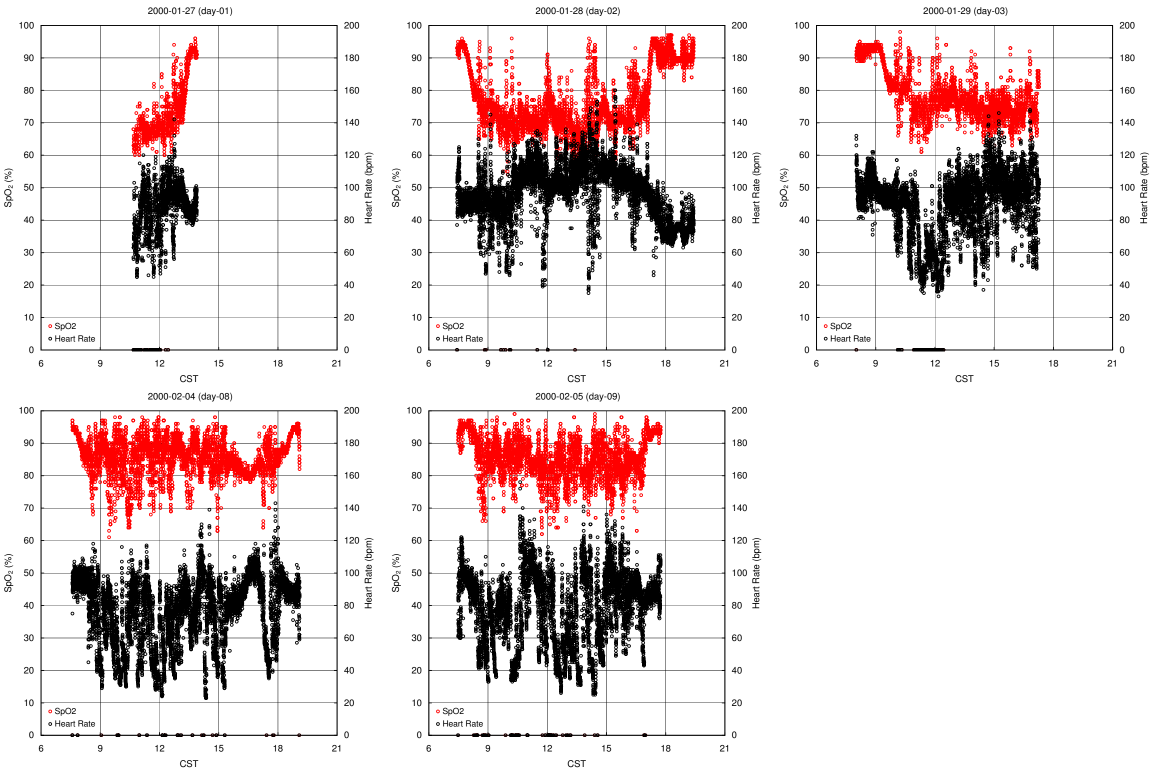

Figure 4: Arterial oxygen saturation (SpO_2: *red*) and heart rate (*black*) during travel from/to San Pedro de Atacama (2450 m) and the Pampa la Bola site (4800 m) on days 1, 2, 3, 8 and 9 of the 2000 January–February visit. Horizontal axis is in Chilean Standard Time without summer time correction (UT − 4h). Note that the readings of the heart rate at high altitude are often erroneous probably due to low perfusion, and those values lower than $\simeq 80$ beats per minute are to be multiplied by ~ 2. In most cases the data cover the entire work day including transportation. During this period, the data for the first part of January 27 and the latter part of January 29 are missing as well as those corresponding to the days 4–7.

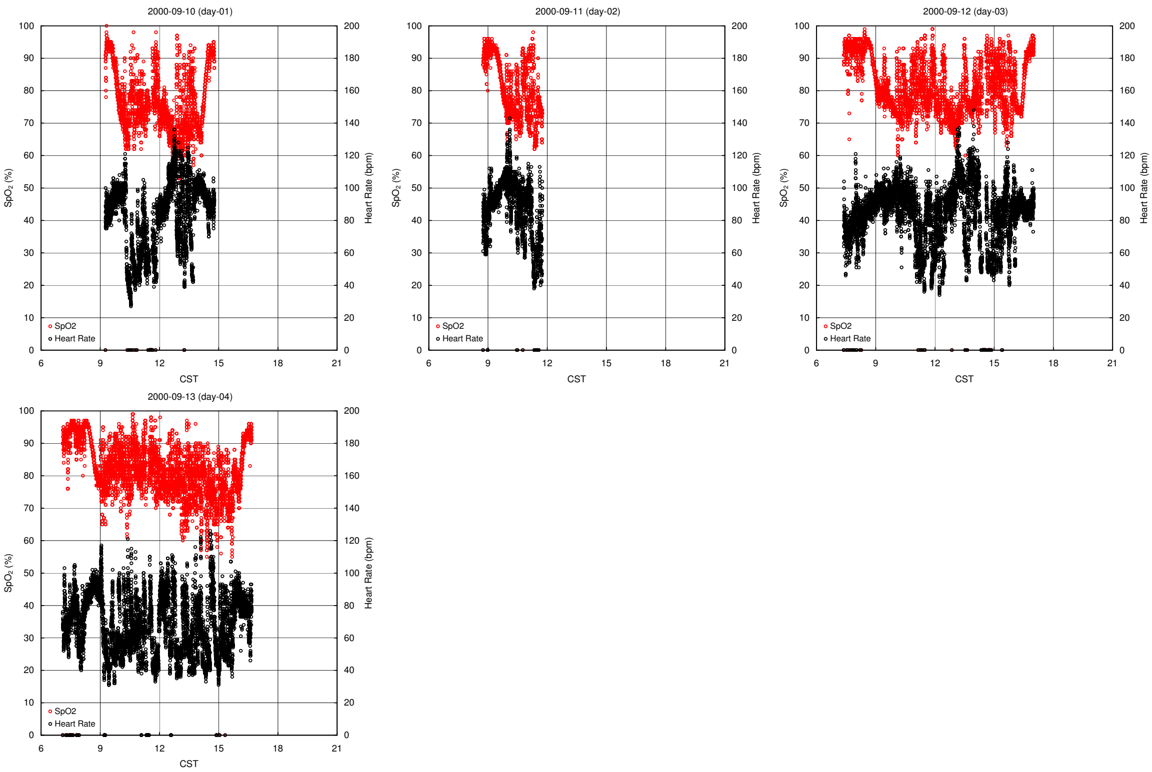

Figure 5: Same as Figure 4 but on days 1–4 of the 2000 September visit. The data for the latter part of September 11 are missing.

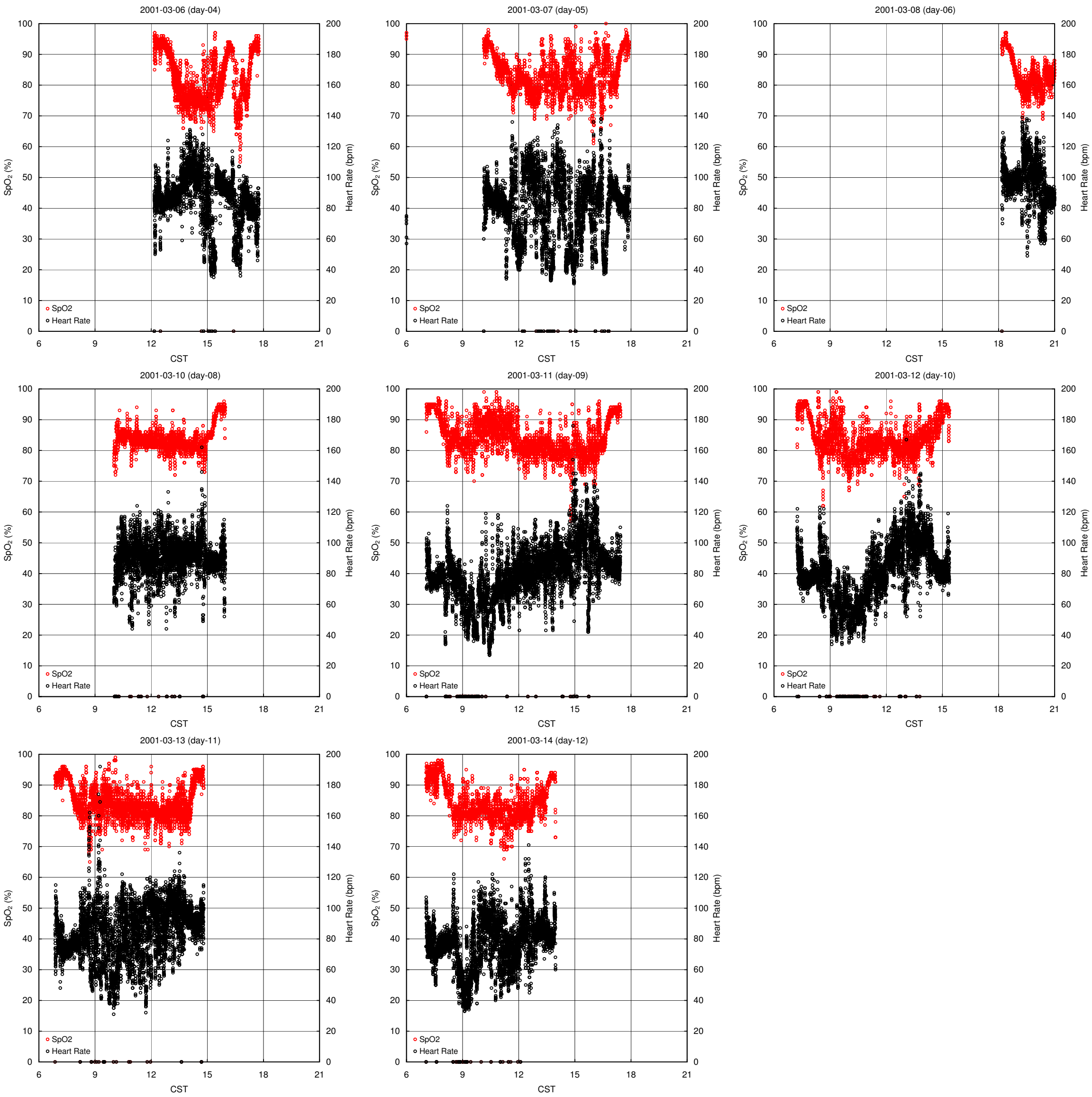

Figure 6: Same as Figure 4 but on days 4–6 and 8–12 of the 2001 March visit. The data for the first part of March 10 are missing. On March 6, 7 and 13, the subject visited the site more than twice a day. Midnight visits were also conducted on March 6, 7 and 13 but the results are not shown here.

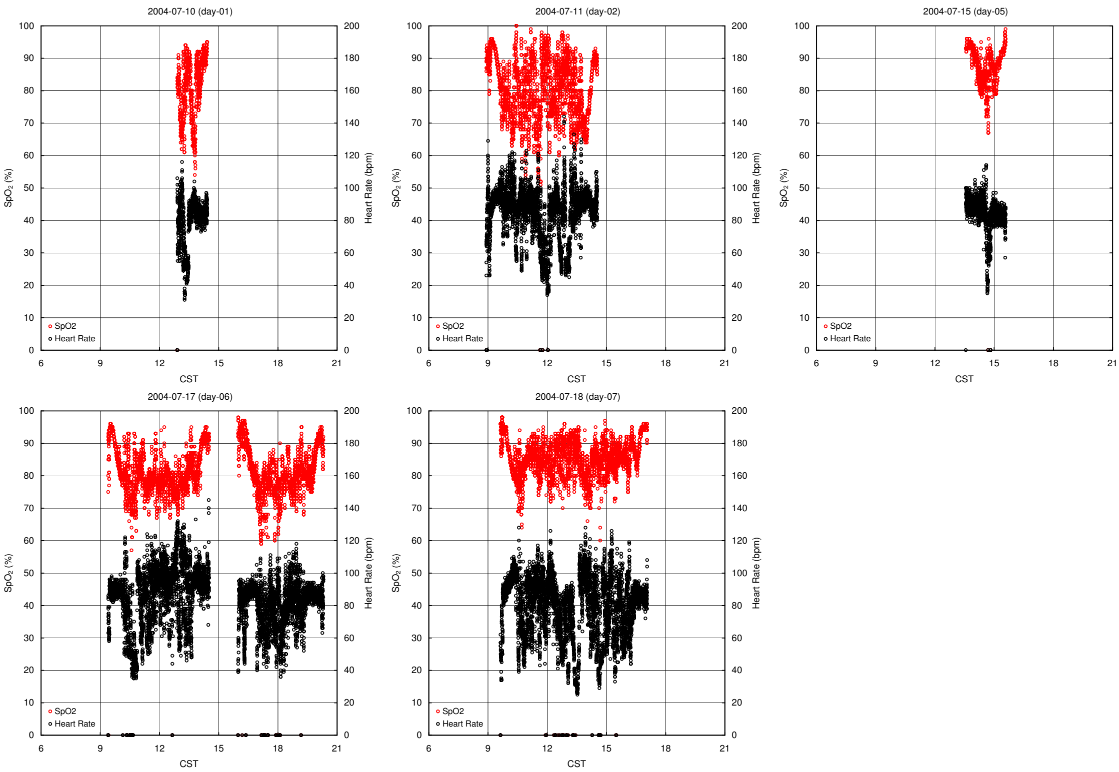

Figure 7: Same as Figure 4 but on days 1, 2, 5, 6 and 7 of the 2004 July visit. On July 17, the subject visited the site twice a day.

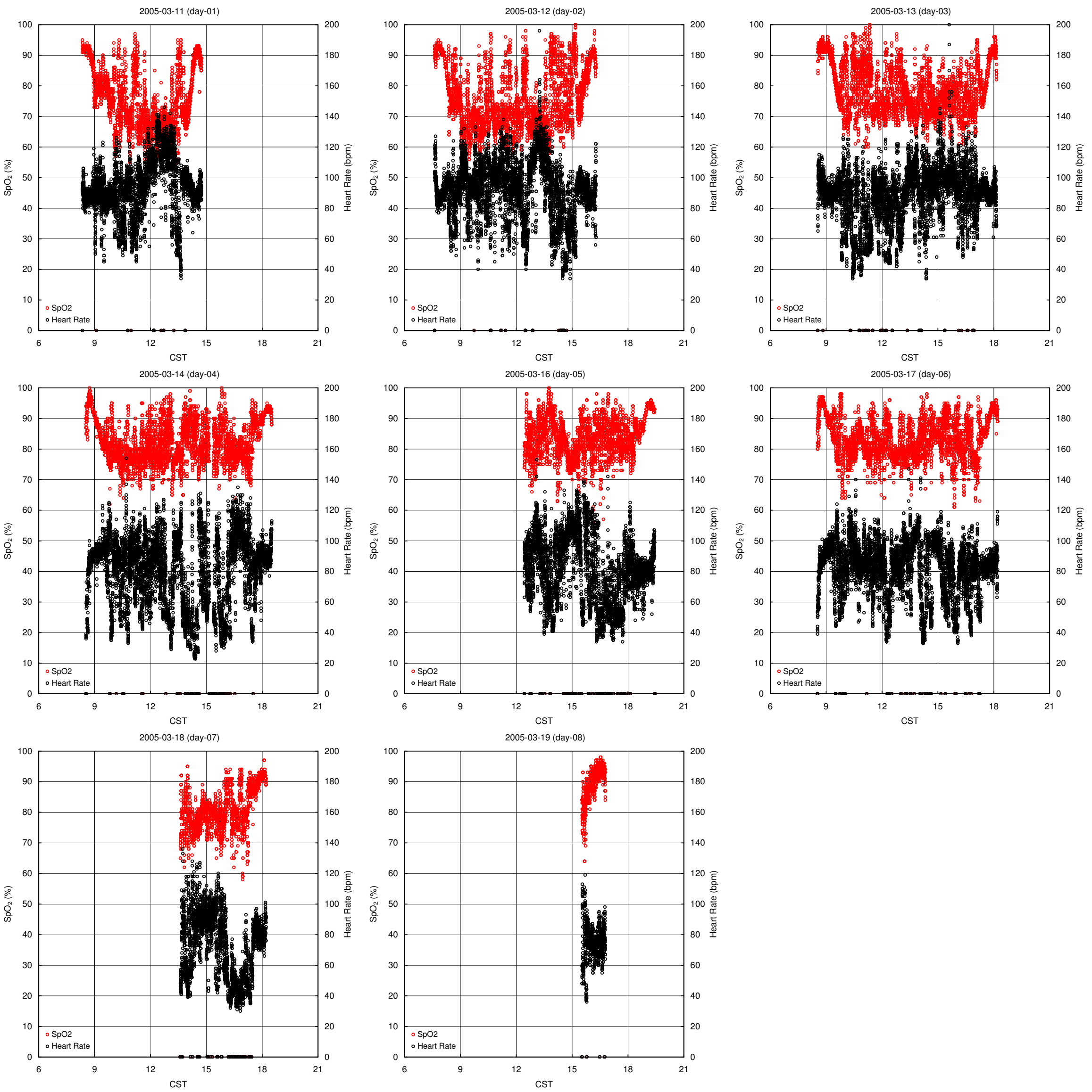

Figure 8: Same as Figure 4 but on days 1–8 of the 2005 March visit. The data for the first parts of March 16, 18 and 19 are missing.

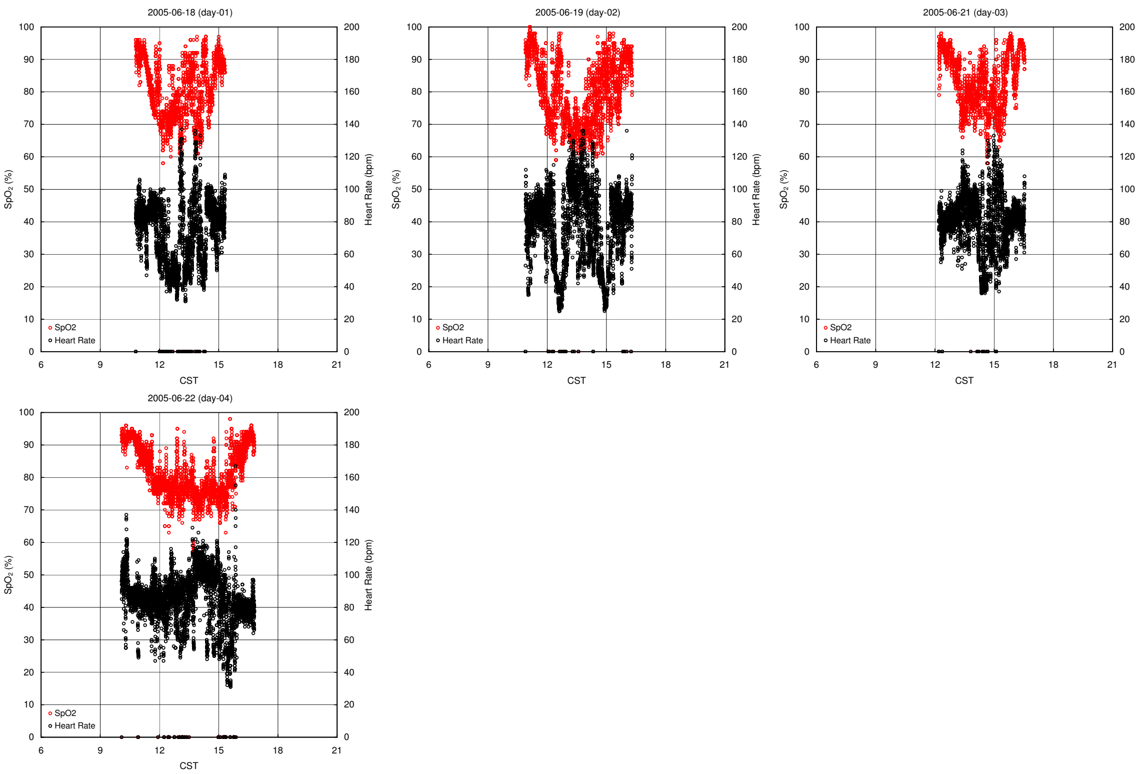

Figure 9: Same as Figure 4 but on days 1–4 of the 2005 June visit.

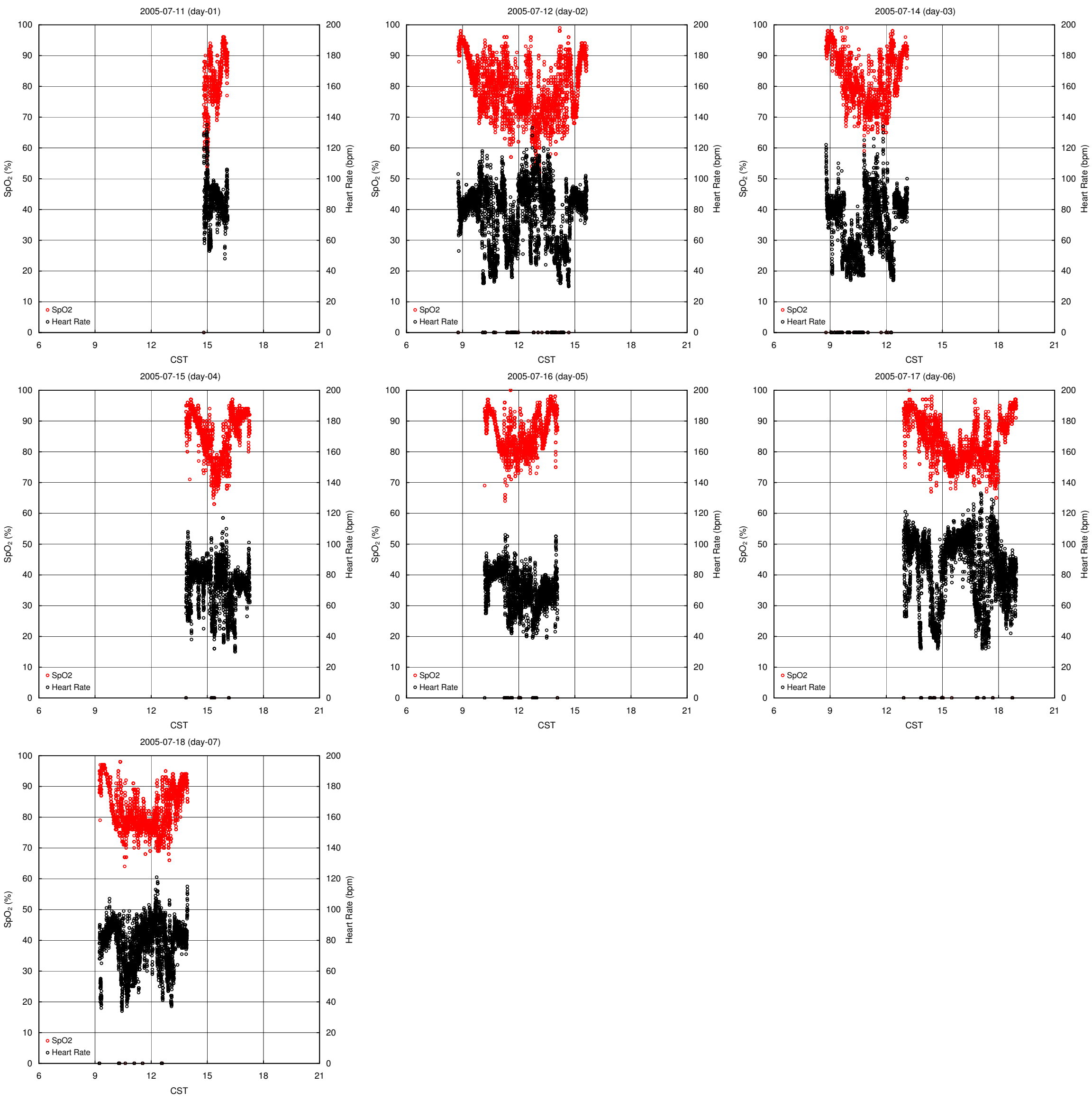

Figure 10: Same as Figure 4 but on days 1–7 of the 2005 July visit. The data for the first part of July 11 are missing.

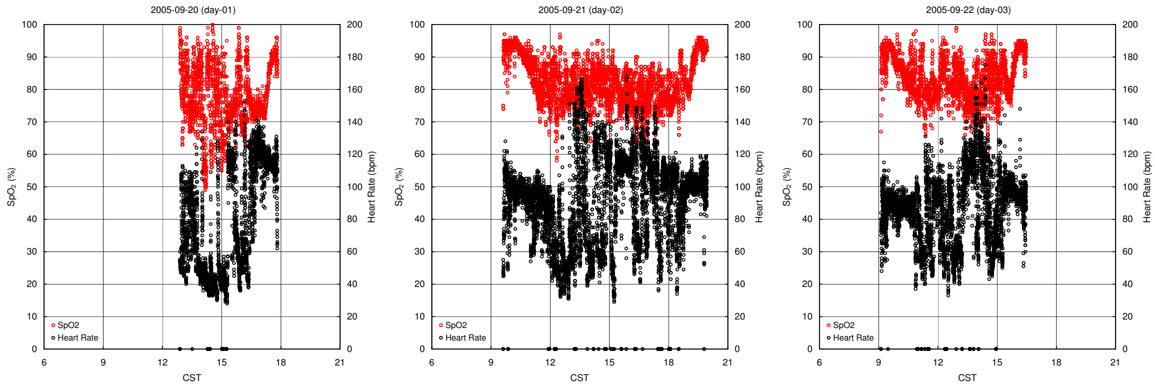

Figure 11: Same as Figure 4 but on days 1–3 of the 2005 September visit. The data for the first part of September 20 are missing.

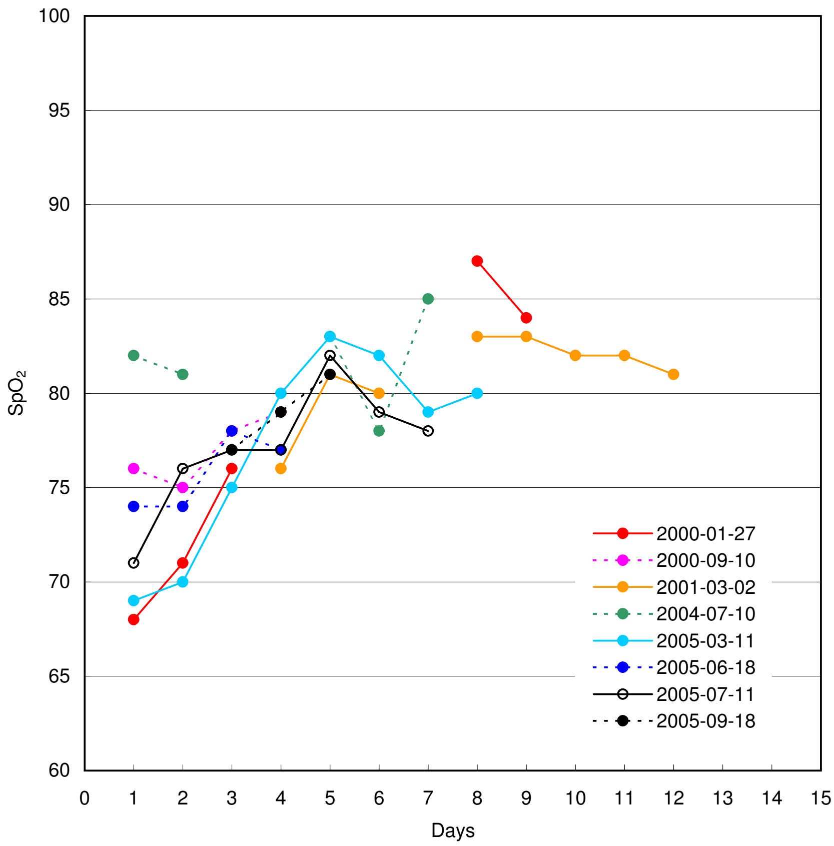

Figure 12: Median values of arterial oxygen saturation measured at high-altitude site as a function of days of acclimatization. Note that, during the 2004 July visit, only light work related to filming was done.