CASE STUDY

PHYSIOLOGICAL STATUS MONITORING IN THE CHILEAN MINE RESCUE OPERATION

A DOCTOR'S VIEW
JEAN ROMAGNOL

The Zephyr™ Remote Monitoring System played a key role in the survival of the 33 Chilean miners while trapped and during their rescue. The system provided essential physiological data as they prepared for their rescue which commenced October 24th, 2010.

When it was announced that the miners were located still alive 17 days after the cave-in, I was in Chile's capital city, Santiago. Immediately, I received a call from one of my associates who noted, from a medical point of view, it might be interesting to monitor the miners while they were trapped.

Previously, I had worked with the Zephyr™ biometric monitoring equipment and software in a project involving the Chilean army. I knew that their equipment would be the best possible solution for the monitoring needs of the trapped miners.

Through cooperation with the U.S., New Zealand, and Chilean governments, all necessary equipment was sent to the aid of the trapped miners.

As I assisted with the rescue, three things became clear:

1. The health of all the miners was compromised due to the constant temperature (91.4 F) and relative humidity of the mine. (98%).
2. They miners were at risk of heat stroke and dehydration.
3. Attempts to cool the temperature in the mine were fruitless.

Because each miner was going to need to train hard to lose weight and prepare for the actual rescue, we needed to overcome these obstacles. First, I increased the miner's overall water intake to stave off dehydration and heat stroke. Second, we outfitted each miner with the Zephyr BioHarness device.

While we were not able to view their vital signs in real time, I was able to recover their data daily to analyze their progress. (Zephyr had devised a system to transmit the data over the fibreoptic voice and data link to the miners. Unfortunately it was not utilized). The process was tiresome, but the information obtained was crucial to save lives, like in the case of Edison Pena, who came dangerously close to hyperthermia. Because we had his data, we were able to immediately reduce his exercise and increase his water intake.

The miner's five-week training program consisted of two phases:

PHASE ONE

The first two weeks focused on two key elements to prepare for the rescue: burning fat and increasing leg muscle.

To burn fat, the miners exercised and maintained a heart rate of 120-140 beats per minute, in which the human body uses primarily body fat as fuel. In order for them to stay in this heart frequency range, the miners were instructed to sing while they exercised. Due to our physiology, we are not able to sing when our hear rate surpasses the 140 beats per minute. This was the perfect way to assure that they were losing sufficient weight to fit in the Fenix II rescue capsule.

Building leg muscle was done with targeted exercises designed to increase their overall leg strength, in case the miner should descend by their own means if the capsule was jammed on the way up the tunnel.

PHASE TWO

The second phase built upon the progress made in the first two weeks. In this dangerous and complicated phase, the miners were pushed to train in the anaerobic-threshold range so as to retard the onset of the threshold; thus lowering their heart rate in response to physical activity. The risks present in this phase were twofold:

1. Ventricular fibrillation: Because the miners were not screened for hidden arrhythmias, pushing them to surpass 160 beats per minute posed the risk of cardiac problems.
2. Exertional heat stroke: High intensity workouts combined with extreme temperatures and relative humidity are very likely to trigger heat stroke.

To avoid those complications, it was mandatory to have the miners monitored at least for heart frequency, respiration rate[1], and temperature[2]. For that purpose, I used the Zephyr OmniSense Analysis software and the Zephyr[3] BioHarness device to acquire reliable and real condition information on

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the miners' response to physical activity in that particular extreme environment. Then, I would contrast it with the predictive physiological behavioral pattern I had developed based in the cardiac and respiratory response to psychological stress and my previous experiences on human response to extreme environments.

Once we determined that the miners were not susceptible to hidden arrhythmias[4], we started to work near the anaerobic threshold of 160 beats per minute. However, to avoid heat stroke and possible joint injury, we never surpassed that threshold.

To further reduce the likelihood of joint or knee injury, knee stabilizer orthesis were sent into the mine. Additionally, they were sent jumping ropes to easily exercise in place. Finally, elastic bands and isotonic resistance training videos to build muscular strength in the biceps, triceps, rhomboids, and deltoids were provided to aid in the miners training.

The final element of this stage was a modified antigravity training called L1 training. L1 training involves a sequential isometric contraction of the lower limb muscles starting at the calf and anterior leg muscles following through the hamstrings and quadriceps muscles, gluteus muscles ending with the abdominals and lumbar muscles. This L1 training squeezes the blood that accumulates in the lower limbs due to gravity and redistributes it to the torso area, assuring adequate brain irrigation and preventing blackouts.

During their training, I designed the human response predictive patterns for both cardiac frequency and respiration rate in response to the psychological and physiological stress during surfacing in the Fenix II capsule. At the same time, the training each member followed was adjusted to its own physiological baseline, as well as how each responded to the mine environment.

The arrival of Ben Morris with additional BioHarness devices represented the consolidation of the medical rescue project, allowing capture of the data while the miners were literally reborn from the depths of the earth, proving to be the only equipment able to withstand the conditions inside the mine. The predictive patterns were precise and the equipment performed wonderfully.

RESULTS

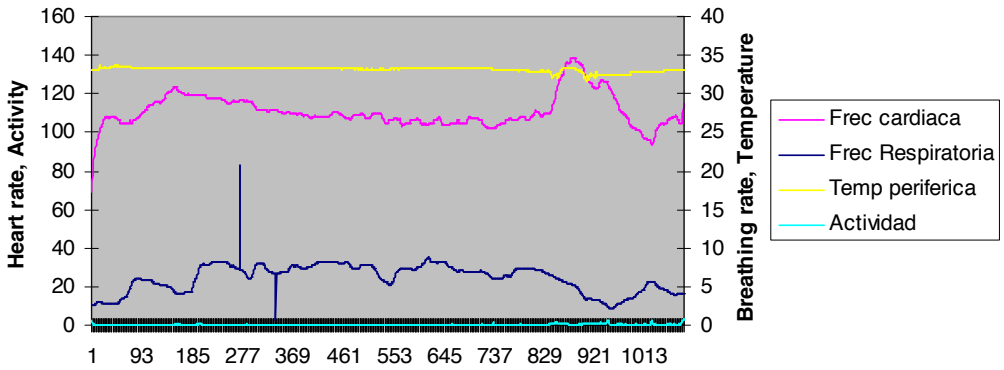
The results obtained in the 5 week workout plan were a considerable weight loss of the miners of 6.5+/-3 kilograms. None of the miners experienced any of the potential problems except for the case of Edison Peña. Edson over-trained himself reaching dangerous core T° level of 40.8°C which required an aggressive rehydration protocol and a pause in his personal training routine.

The other case that didn't behave as expected was Mario Gomez, the eldest miner, who had Silicosis and Lung Fibrosis and was suffering from a pneumonia that affected the lower half of his right lung. This affected his response to cardiac activity, making him the only case that surpassed the predicted heart rate value of 150 bpm during the rescue. His heart rate rose to 151 beats per minute, totally explainable due to his condition.

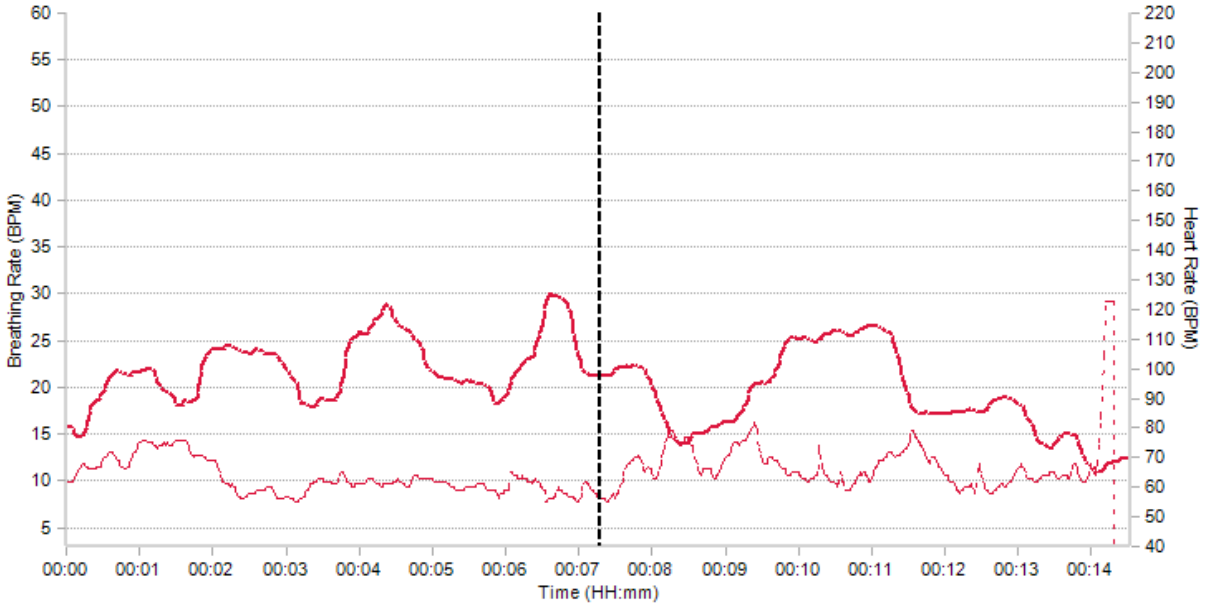
The results of our efforts were realized. Every miner fit in the Fenix rescue capsule and every miner surfaced in adequate fitness condition and was discharged from the hospital within 2 days of the rescue.

Minimum heart rate	78+/- 3 beats per minute
Mean heart rate	108 +/- 4 beats per minute
Maximum heart rate	127 +/- 3 beats per minute
Minimum breathing rate	9 +/- 1,3 breaths per minute
Mean breathing rate	24,42 +/- 2,1 breaths per minute
Maximum breathing rate	32,5 +/- 2,8 breaths per minute
Mean Skin T°	33,6 +/- 0,35
Activity	0,92 +/- 1,18

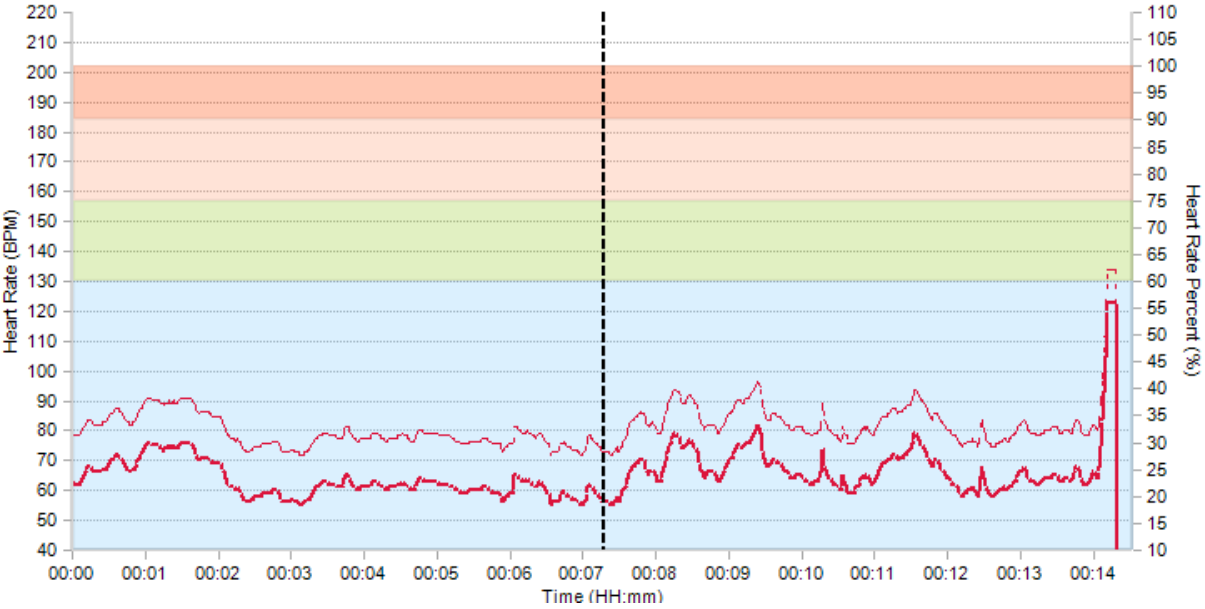
VITAL SIGNS DURING THE RESCUE:



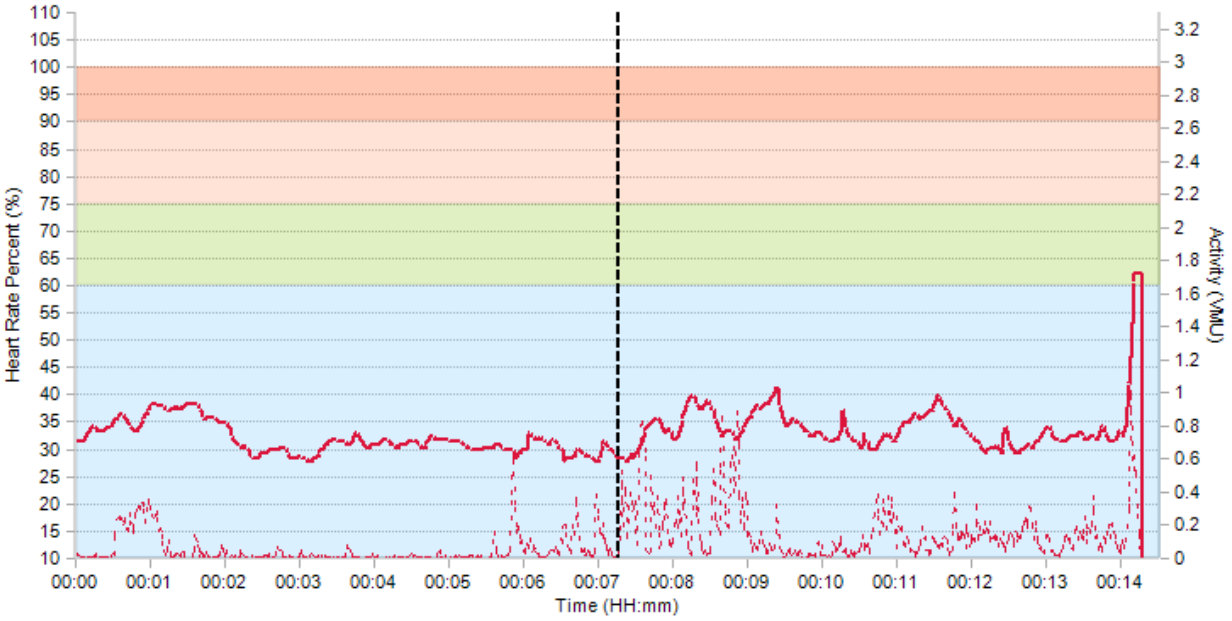
CARDIAC AND PULMONARY RESPONSE TO EXERCISE:



CARDIAC AND HEART RATE MAX % RESPONSE TO PSYCHOLOGICAL STRESS (RESCUE):



HEART RATE MAX % RESPONSE TO ACTIVITY:



As shown in these graphs, vital signs observed during the rescue evidenced that the miners had a significant cardiac and respiratory reserve in the moment of the rescue, managing themselves within the physiological safety range in those variables, and having been able – if needed – to perform at higher intensity and stress levels.

The survival of the 33 miners was neither a miracle nor sheer luck, but it was medical science at its best. We managed every detail of the miner's health status, as well as their response to the psychological and physiological demands necessary to conduct the rescue mission. This was made possible through the collaboration of accurate physiological behavior predictive designs and forecasts, as well as access to physiological status monitoring equipment. In the end, we were able to accurately measure and monitor the overall status on the miners, making life-saving changes to routine in realtime.

This experience revealed many ways to benefit miner safety in the mining industry, allowing us to see new and dynamic ways to measure life in the most extreme conditions.

1. Respiration rate to determine the heart frequency at anaerobic threshold, and consequently to set the heart rate range for each miner.
2. Since the Zephyr monitor measures only skin temperature I had to adjust the result by applying the following formula **Core T°=37+1+(1*(4/(External T°-Skin T°)/10)) (1,2*(Heart rate-120)/15))**. The core temperature formula applies when no type of special barrier is applied between the person and the external temperature. In case of T° below 0° one should add the value to the value of the skin temperature. The result is expressed in Celsius.
3. All the equipment used in the rescue was donated to the rescue by Zephyr Technologies.
4. I used the R-R visualization tool present in the Bio Harness software application, to discard arrhythmic patterns, based in the patterns these particular arrhythmias show in the EKG in terms of length of the R-R complex alterations.

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