MONITORING THE CARDIORESPIRATORY SYSTEM DURING LONG-TERM EXPOSURE TO MICROGRAVITY

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ABSTRACT

A simple protocol is proposed to monitor the cardiorespiratory system of the crew members of the International Space Station. It requires minimal training and it can easily be integrated in their off-duty time in space. Some preliminary results on the monitoring of the crew of the recent STS-90 Neurolab mission are presented. Based on our experience during this mission, we think that an efficient collaboration via the Internet is readily feasible in order to assess the acquired data quality and to evaluate a set of physiological parameters on a routine day-to-day basis. Concerning long duration recordings such as sleep studies, the need for reliable advanced signal processing is emphasized.

Key words: cardiorespiratory physiology; daily monitoring; telescience.

1. INTRODUCTION

Maintaining the health is of considerable importance for the crew members of the International Space Station (ISS) and of other long duration space flights. Furthermore, in the perspective of a future Mars mission, the effects of the readaptation to gravity have to be studied. The day-to-day follow-up of the cardiorespiratory parameters of the astronauts will provide valuable indications of their ability to adapt to microgravity (μG), their evolution during long-term exposure to μG and their readaptation to gravity.

In this contribution, we propose a simple protocol to monitor the cardiorespiratory health of the astronauts during the early utilisation phase of the ISS. Preliminary results from the recent STS-90 Neurolab mission are presented in order to show that an efficient collaboration via the Internet allows for the evaluation and follow-up of a set of physiological parameters of the astronauts. After a brief presentation of our Neurolab experiments as a whole and a summary of the tele-operations involved, results of the noninvasive measurement of the heart rate and respiratory movements are discussed. These results were ready for assessment by the mission scientists in Houston at most 24 h after the measurements were made. Hence, the feasability of the day-to-day monitoring from a remote site is demonstrated. Building on this experience, a simple, noninvasive protocol is proposed which interferes as little as possible with the daily schedule of the ISS crew and which demands almost no preliminary training. Its implementation will allow us to follow the adaptation of the crew to μG and to evaluate the effect of the physically demanding work which they will perform building the station, which will include an important amount of extra-vehicular activity.

2. STS-90 NEUROLAB

2.1. The Mission

The Neurolab mission (STS-90) on board of space shuttle Columbia was launched on April 17, 1998, and landed at Kennedy Space Center on May 3. During this 16-day mission the experiment 'Sleep and Respiration in μG' (Principal Investigator : J. West, University of California at San Diego) was carried out in order to gain a better understanding of the effect of gravity on the respiratory physiology (ALFE : Astronaut Lung Function Experiment) and to study the astronauts during sleep.

Table 1 lists the total duration of the acquired signals during the ALFE sessions. After calibration of the

Table 1. Monitoring data for the STS-90 Neurolab crew.

subject	recorded signals (h:mm:ss)		
	preflight	during flight	postflight
S1	1:14:10	0:39:06	1:20:24
S2	1:09:01	0:29:20	1:27:59
S3	1:01:23	0:39:08	1:15:39
S4	0:58:39	0:39:08	1:27:24
S5	1:16:39	0:37:05	1:30:34
Mean	1:07:58	0:36:45	1:24:24

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equipment, a number of respiratory protocols were performed by the subject, of which the following are of interest for us here :

- CT1 : controlled tidal breathing of approximately 0.5 l, i. e. inspiration at a rate of 0.25 l/s during 2 s;
- CT2 : controlled tidal breathing at the same rate but for 4 s, hence a volume of 1 l;
- ROC : resting open circuit, i. e. spontaneous tidal breathing.

Note that, for all experimental protocols, the breathing was performed on a mouthpiece. During baseline data collection the same experimental protocol was performed in supine and in standing position. The following parameters were measured noninvasively during the different protocols :

- Respiratory : rib cage and abdomen movements by respiratory inductive plethysmography (RIP), inspiratory flow, gas concentrations;
- Cardiovascular : arterial blood pressure (Finapress) and oxygen saturation at finger tip, electrocardiogram (ECG).

The acquired data was stored on board for backup and replay and the signals were transmitted to mission control as far as downlink availability allowed. Concerning the sleep data, a small lightweight acquisition unit was attached to the instrumented astronaut which monitored the respiratory movements, arterial oxygen saturation, electroencephalogram, electro-oculogram, ECG and temperature during his sleep.

2.2. Telescience Support

The telescience set-up which was dedicated to the ALFE data, consisted of two file transfer protocol servers, one at either side of the Atlantic. Once the team in Houston received the data and passed it through a first signal quality filter, the different files were encrypted by asymetric key encryption and posted on both servers. This encryption served three purposes simultanuously, namely to compress the data and to ensure the confidentiality and integrity of the transmitted files. On arrival of the data, the Brussels group produced a report the next day (night at Houston) which was sent back by electronic mail. This report contained, for each subject and experimental protocol, besides signal statistics, the mean and standard deviation of the following physiological parameters :

- Respiration : respiratory frequency (Hz), inspiration volume (l), inspiration flow (l/s), ratio of inspiratory time to respiratory cycle (T_i/T_{tot}), relative contribution of the abdominal movement to the total respiration volume ($\Delta V_{ab}/\Delta V_{tot}$, %), mean phase difference between abdominal and rib cage movements (°);
- Heart rate : RR interval (RRI, s);
- Arterial blood pressure (mmHg) : diastolic and systolic pressure, pulse pressure ($p_{pulse} = p_{systolic} - p_{diastolic}$) and mean pressure ($p_{mean} = (p_{systolic} + 2p_{diastolic})/3$).

In addition, some other overall measures for the heart rate variability (HRV) were calculated, namely the total spectral power density, the spectral power density in the low frequency range (LF : $0.04 \leq f < 0.15$Hz) and in the high frequency range (HF : $0.15\text{Hz} \leq f < 0.4$Hz) and the ratio of both (LF/HF) (Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology 1996).

Table 2 shows the telescience statistics. It is seen that the amount of data which was transferred was quite limited. Every subject was monitored on average for about 14 minutes per session. The last column shows the amount of data which was unavailable due to loss of signal episodes (LOS) during flight. Although originally intended to check the performance and calibration of the equipment in order to evaluate if the data would be analysable, we are aware of the potential of this kind of collaborative effort in the sense that it allowed the Houston/San Diego team to concentrate on the operations while being updated on the data quality and on the evolution of some physiological parameters of the crew.

2.3. Preliminary Results

Heart Rate (HR) Figure 1 shows the variation of the mean (±SD) of RRI with respect to the subject's preflight mean for the different experimental sessions under the ROC protocol. The three subjects which are shown, are those for whom a complete set of analysable measurements at 1 G in standing position were obtained. Good agreement is obtained with the study of Fritsch-Yelle et al. (1996) who observed on 12 male astronauts from different shuttle missions that :

- the mean RRI increases (reduced HR) and variability decreases in μG;
- on return from space, the mean RRI remains lower (higher HR) than the preflight values for several days.

Although an increased RRI during flight and some adaptation after return can be clearly observed, the intersubject variability is too large to allow statistically founded conclusions. This variability can be due to a lack of control of the experimental circumstances but may also be due to the fact that the samples, i. e. the RRI recordings, are not stochastic in the sense that their value are not independent from each other. Hence, an analysis dedicated to the HRV is needed, which by its nature is immune for changes in mean RRI if the signal is sufficiently stationary, and which can reveal underlying mechanisms for this variability.

Table 2. Telescience statistics for the STS-90 Neurolab mission.

session	transmitted files	size(1) (Mbyte)	transmitted signals (h:mm:ss)	recorded signals (h:mm:ss)	data loss (%)
preflight(2)	553	76.234	5:39:50	5:39:50	-
during flight					
F04	30	5.698	0:35:11	0:48:56	28
F06	47	11.553	0:23:48	0:37:06	36
F11	81	19.740	0:48:55	0:48:55	0
F15	74	19.006	0:45:17	0:48:52	7
postflight(3)	735	91.698	7:02:00	7:02:00	-
Mean(4)	~23	3.445	0:14:04	0:14:33	18(5)

(1)After encryption and compression.
(2)Preflight sessions are L90 (90 days before launch), L60, L30 and L15.
(3)Postflight sessions are R01 (1 day after return), R02, R04, R05 and R15.
(4)Per session per subject.
(5)Inflight sessions only.

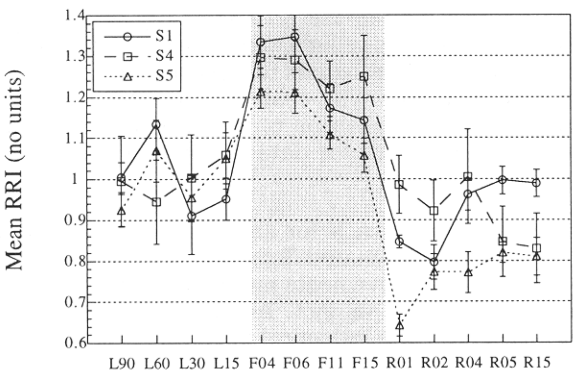

Figure 1. Mean±SD of th RRI of 3 subjects during unconstrained tidal breathing on a mouthpiece (ROC), as a function of the different experimental sessions in chronological order. Preflight : L90 (90 days before launch), L60, L30, L15. Inflight : F04 (flight day 4), F06, F11, F15. Postflight : R01 (1 day after return), R02, R04, R05, R15. Pre- and postflight measurements were taken in standing position.

The spectral analysis of the HRV is known to be a noninvasive method for monitoring the autonomic regulation. In particular, the ratio of the spectral power density in the LF to the HF range is recognized to be a measure for the balance between the ortho- and parasympathic nervous system (e.g., Fritsch-Yelle et al. 1994). Figure 2 shows the normalized LF/HF to the subject's mean preflight value as a function of the session for the same three subjects as in figure 1. The spectral analysis was performed as follows. After removal of extrasystoles and artifacts the RRI signal is interpolated with a cubic spline in order to obtain a regular spacing in time. Detrending with a third order polynomial was performed prior to the Fast Fourier Transform with a Hanning window. Periodogram-based spectral estimates were computed by using the Welch method : data were segmented in 60 s sections and spectral analysis was performed on successive time windows with 50% overlap between them. Finally, the results were averaged. By a two-way analysis of variance it was established that the intra-subject variability does not explain the observed variance between pre-, in- and postflight results. Scheffé's multiple comparison procedure yields significantly different means between all three categories ($P < 0.05$). It is clearly seen that after landing an adaptation time is needed. The one-way analysis of variance of the postflight sessions seperately yields that only the R15 session is not significantly different from the preflight results whereas all the other sessions are with $P < 0.05$. Our

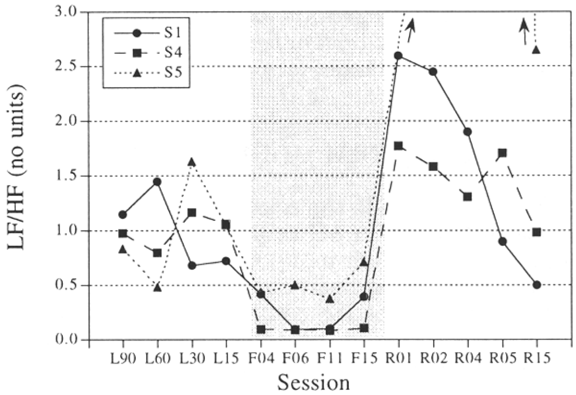

Figure 2. LF/HF spectral power density ratio normalized to the subject's preflight mean for the CT1 protocol as a function of the experimental session in chronological order. Pre- and postflight measurements were taken in standing position. For clarity, the three values for S5 at days R02 (= 4.53), R04 (= 6.74) and R05 (= 9.02) are not displayed.

observations are in good agreement with the study of Fritsch-Yelle et al. (1994) who observed this adaptation phenomenon in 16 astronauts on several shuttle missions. They suggest that during space flight, the lack of stimuli to the baroreceptors impair the ability to respond to these pressure changes. At least one week is needed to readapt to gravity (Fritsch-Yelle et al. 1994). A major drawback of this conventional LF/HF analysis is that it requires a constant breathing frequency which is situated in the HF range. This requirement is met in the CT1 protocol. Our group has however developed a methodology to ease this restriction (Migeotte & Verbandt (1998)), which could lead to the more general application of this technique, in particular during quiet, uncontrolled tidal breathing, such as during sleep. It consists of normalizing the time variable of the RRI signal with respect to the instantaneous respiratory frequency. Hence, variations in respiration rate are filtered from the RRI signal.

Respiration Figure 3 shows $\Delta V_{\mathrm{ab}}/\Delta V_{\mathrm{tot}}$ which is normalized for the subject's preflight mean value as a function of the different experimental sessions. This result is consistent with our observations on the Euromir 95 and D2 missions which showed an average increase of 27.6% between 1 G and 0 G (Wantier et al. 1998).

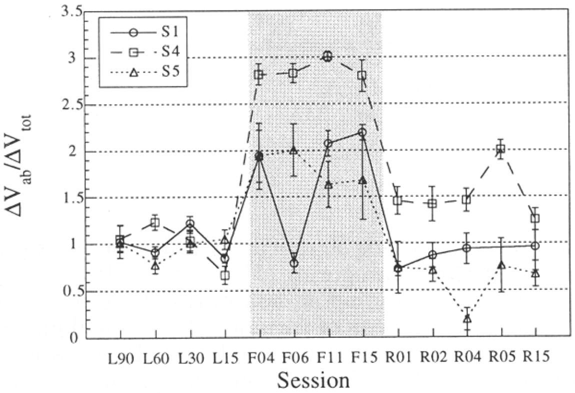

Figure 3. Relative contribution of the abdominal movement to the total respiratory volume ($\Delta V_{\mathrm{ab}}/\Delta V_{\mathrm{tot}}$) normalized to the subject's preflight mean for three subjects performing the CT1 protocol as a function of the experimental sessions (see caption figure 1). Pre- and postflight measurements were taken in standing position.

3. LONG-TERM MONITORING ON ISS

The ISS will provide the scientific community with a unique test bench in μG to perform log-duration experiments. Although many studies on sustained exposure to μG have been conducted during different space programs, the ISS could enable scientists to obtain more systematic recordings on subjects. In the context of the early utilisation phase of the ISS and with the experience gained from previous missions, more than the daily follow-up of some cardiorespiratory parameters of the crew will be unpractical to implement. We are aware that the crew members will have a heavy schedule building the station. Hence, in order to minimize the inflight crew time and preflight training, we propose a simple measurement protocol which consists of :

1. Instrumentation of the subject with 3 electrodes, a RIP suit, a pulse oximeter cuff and an arterial pressure measuring device at the finger tip.
2. Actuation of the data acquisition.
3. Calibration of the RIP by tidal breathing in a handheld flow meter.
4. Calibration of the pressure measurements by means of an automatic brachial pressure measurement.
5. Quiet tidal breathing during resting period (few minutes).
6. Maintaining logs of observations regarding the instruments and the feeling of the subject.
7. Removing data storage device from the acquisition unit and mounting an empty one for the next session.

With rest, we mean that the monitoring occurs during the leisure time of the astronauts when they read or watch a video. Due to the sensitivity of the RIP to movements, we would prefer that the subjects keep a fixed spine attitude. However, algorithms for movement detection are being developed in our laboratory which will enable the filtering of these artifacts. A video surveillance of the subject would be helpful in this respect. One should keep in mind however that any spectral analysis will be limited in terms of minimal detectable frequency component by the duration of the recording.

With current state-of-the-art technology, it is readily feasable to develop a lightweight acquisition device which transmits the signals to a central unit via wireless transmission. The central computer will then serve as a data acquisition unit and will perform the necessary operations for data logging and downlinking.

One remaining obstacle for an efficient and complete analysis is the automated detection of artifacts in the signals, such as movements and drifts which indicate a not quite relaxed subject. Advanced analysis methods based on artificial neural networks are being developed to cope with this problem in order to fully automate the analysis of these long recordings. These advanced signal treatment and evaluation algorithms can, when properly validated, be implemented in the acquisition unit on board to provide the astronauts with a personalised tele-health management system.

4. ACKNOWLEDGMENTS

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