ALTERATIONS OF SOURCE AND CONNECTIVITY EEG PATTERNS UNDER SIMULATED DEEP-SEA CONDITION

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ABSTRACT

New wireless technologies can overcome technical and safety problems of older ones for recording biological signals in hyperbaric chamber. In an application of a Bluetooth system, we measured the electroencephalographic (EEG) activity in professional divers in a hyperbaric chamber to determine how oxygen affects the brain activity. The cortical sources and the connectivity of the EEG rhythms were estimated in three conditions: breathing air at sea level; breathing O_2 at a simulated depth of 18 msw; breathing air at sea level after decompression. The oxygen condition was characterized by an amplitude increase in the alpha and beta sources in the parietal and occipital areas and decrease in the occipital delta and theta sources for at least 20 mins, with a parallel disconnection of the frontal-parietal links in the early minutes of O_2 breathing. These results may be relevant for establishing a reference point in future studies on oxygen-sensitive subjects.

***Index Terms*—** Bluetooth, EEG, hyperbaric chamber, oxygen toxicity, signal processing, brain connectivity

1. INTRODUCTION

Since the 1970s, signal recording in hyperbaric chambers has presented numerous practical challenges in the evaluation of biological parameters in operational situations of professional divers. The main limitation is that the chamber is enclosed in a steel casing that shields against electromagnetic waves entering from the environment and blocks the electromagnetic waves generated inside from propagating outside. The second limitation is that the power supply of equipment inside the chamber cannot be powered by alternating current as it may generate sparks, creating a considerable safety hazard.

Till now, the main problem with the steel casing shielding electromagnetic wave propagation has been solved by running wire connections from the biological signal sources to outside the chamber. With the development of the Bluetooth communication protocol, signal transmission via low-length radio waves obviated the need for cables. The Bluetooth low-length radio waves can pass through the resin portholes of the hyperbaric chamber walls (Figure1A).

The use of an oxygen mixture and closed-circuit breathing apparatus for diving at various depths augments the risk of central nervous system oxygen toxicity (CNS O_2T). The electroencephalogram (EEG) pattern is known to significantly change during saturation dives [1]. Oxygen poisoning can manifest itself with a range of symptoms and complications as well as EEG alterations. Prompt recognition of the earliest symptoms, as described after dry or humidified hyperbaric oxygen exposure, is vital. The exploitation of the Bluetooth technology in hyperbaric chambers provides a viable solution for monitoring divers' conditions.

Recently, the investigation of brain networks both at rest and in relation to a particular condition or task has been gaining increasing attention. Functional connectivity analysis consists in the investigation and modeling of the relationships between brain regions by extracting relevant or significant aspects of network organization.

In this study we present an application of a Bluetooth device that allows the recording of biological signals in a hyperbaric chamber. Thirtytwo-channel EEG was recorded with a Bluetooth EEG system in 11 professional divers. A 20-min EEG recording was carried out under three different experimental conditions: air (baseline at sea level, 1 atmosphere absolute pressure [ATA]); oxygen breathing (at a simulated depth of 18 msw, 2.8 ATA); and air (after decompression, 1 ATA). The aim was to determine how oxygen, assumed at a constant hyperbaric pressure of 2.8 ATA, affects the bioelectrical activity, in terms of cortical sources and brain connectivity in professional divers as compared to pre- and post-oxygen breathing.

2. METHODS

2.1. Device description

The study was conducted using a portable EEG recorder connected via Bluetooth wireless transmission to a notebook that

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visualizes the EEG signal.[1] The Bluetooth EEG system includes a cap with 32 channels, an acquisition unit, and a data processing and storage unit. The EEG cap[2] is composed of Ag/AgCl electrodes and adjusted so that 18 (placed on the nasion), Cz, Oz, and the pre-auricular points were correctly placed according to the international 10/20 system. The data were recorded against a vertex electrode reference (Cz) at a sampling rate of 250 Hz and subsequently re-referenced using the average reference.

2.2. Experimental protocol and EEG data

The hyperbaric chamber used in the study complied with Italian Navy standards for safety equipment and emergency procedures. The study population consisted of 11 healthy male navy divers (mean age, 46.2±4.9 years). Exclusion criteria were a medical history of respiratory problems, sleep disturbances, smokers, and overweight. The internal ethics committee of the University approved the experimental protocol, and written informed consent was obtained from the subjects.

Each recording session lasted 20 mins, during which the subject was reclined on a cot with eyes closed. A baseline 20-min EEG recording was made at 1 ATA breathing air (AIRpre) in an open chamber. A 2-min compression profile (descent rate, 9 m/min) breathing air was used to reach the oxygen stage at a pressure of 2.8 ATA. At this pressure, the subject breathed pure oxygen via an oronasal mask (O_2) and a second 20-min EEG recording was acquired. The atmosphere within the hyperbaric chamber was controlled to maintain a total pressure of 2.8 ATA. After decompression, back on air breathing, the EEG of each subject was recorded for 20 mins (AIRpost), discarding the first 2 mins (ascent rate, 9 m/min) (Figure1B). Visual inspection of the EEG signals showed no abnormalities. The EEG data were preprocessed as described in [1]. The data for each condition (20 mins for each) were divided into epochs of 2 s. The analysis was done separately in the following six bands: delta (1.5−6 Hz), theta (6−8 Hz), alpha (8−12 Hz), beta1 (12−18 Hz), beta2 (18−21 Hz), and beta3 (21−30 Hz).

2.3. Cortical source analysis of the EEG rhythms

In order to localize the cortical sources of scalp EEG activity, standardized low-resolution brain electromagnetic tomography (sLORETA) was used [2]. In frequency domain, LORETA can be computed from EEG cross-spectra. For a given subject, let $\Phi_{i,t}$ denote a vector comprised of the scalp electric potentials measured at each scalp electrode, at time instant t ($t = 1, ..., N_\tau$), and for EEG epoch i ($i = 1, ..., N_\epsilon$). Let $\Phi^\Omega_{i,t}$ denote the band filtered EEG, where Ω denotes the frequency band of interest. The instantaneous current density

[1]EBNeuro - ATES Medica Device, Verona, Italy.

[2]Electrical Geodesic Inc., OR, USA.

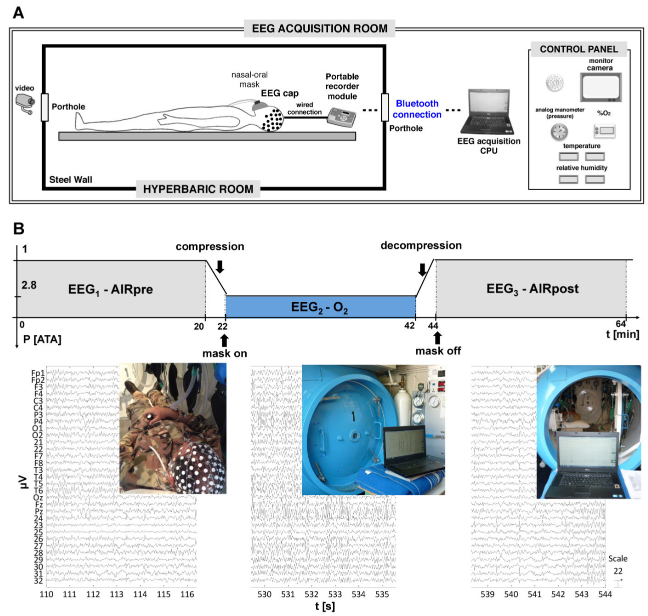

Fig. 1. (A) Experimental setting and EEG Bluetooth technology. (B) Dive profile and recording sessions.

estimate is computed as the linear transformation:

$$\hat{J}^\Omega_{i,t} = T\Phi^\Omega_{i,t} \quad (1)$$

where T denotes the inverse of the transfer matrix or lead field matrix K. The LORETA image for the frequency band Ω is then defined as the spectral density of estimated current density signals [3]. Under the three conditions, for each subject separately and all subjects together, the EEG cross-spectra and then the corresponding 3D-cortical distribution of the electric neuronal generators were computed with sLORETA for each frequency band. The spectral current density was mapped into a 3D representation: one map for each frequency band in the AIRpre condition (1 −20 mins) and seven maps for the O_2 and AIRpost conditions, with seven intervals of analysis (1', 2', 5', 8', 11'−12', 16'−17', and 19'−20'). Minutes 19−20 from the EEG of subject no. 3, minute 5 from subject no. 8, and minute 2 from subject no. 9 were discarded due to loss of the EEG signal via Bluetooth.

Statistical analyses were performed using the sLORETA software package. The difference in source localization of cortical oscillations between the three conditions in each frequency band was assessed by voxel-wise independent sample t-tests based on sLORETA log-transformed current density power. In the resulting statistical 3D images the cortical voxels showing significant differences were identified by a non-parametric approach (statistical nonparametric mapping) via randomizations [4]. The LORETA images were statistically compared between conditions (O_2 vs AIRpre, AIRpost vs AIRpre). The t-values corresponding to $p < 0.05$ were plotted onto a magnetic resonance imaging template.

2.4. Effective connectivity

The brain connectivity describes how brain regions are connected and the knowledge about interaction may provide new insights into the physiology underlying the process. The effective connectivity is defined as the influence that one neural system exerts over another, taking into account the direction of the information flow. In particular, the measure of directed transfer function (DTF), based on multivariate autoregressive (MAR) models, has been developed to describe the causality among an arbitrary number of signals. The DTF was here applied to EEG data in the frequency ranges described above and the connectivity pattern was computed using the MATLAB toolbox eConnectome [5]. The DTF was constructed out of the transfer matrix of the system (H):

$$DTF_{i,j}(f) = \frac{H^2_{i,j}(f)}{\sum_{k=1}^{K} H^2_{i,k}(f)} \tag{2}$$

where $DTF_{i,j}(f)$ represents the information flow from signal x_j to signal x_i, K is the number of channels and $H_{ij}(f)$, the inverse of the frequency-transformed matrix of MAR coefficients, contains information about the causal relation from signal x_j to signal x_i at a frequency f. The most representative channels were selected for the analysis: F3, Fz, F4, C3, C4, P3, Pz, P4, O1, O2, T3, T4, and 28. A non parametric method based on surrogate data was used to assess the significance of the estimated connectivity measures [6], in order to remove the links that formed spurious interactions between EEG channels. Only statistically significant links were reported.

3. RESULTS

3.1. Source imaging

As compared to baseline, during O_2 breathing, the brain activity showed a rapid and significant decrease in delta and theta sources in the posterior regions starting from the early minutes and a parallel significant increase in the alpha and beta1 sources in the same regions (Figure2A). As shown on the t-maps (O_2 vs. AIRpre), a significant decrease was detected for the theta sources and persisted throughout the entire recording during O_2 breathing. The alpha sources markedly, albeit less significantly, localized in the same posterior regions. The beta2 and beta3 bands were less involved (Figure2B). After decompression (AIRpost), the delta and theta sources significantly decreased from baseline (AIRpre) principally over the posterior regions until minute 5. At 11'−12', the decrease was still present but less significant over the posterior regions. After 20 mins, the power resembled that of AIRpre even though a complete recovery to the baseline was not observed (Figure2A). This modification is shown on the t-maps (AIRpost vs. AIRpre). The alpha and beta1 sources significantly increased in the same posterior regions during

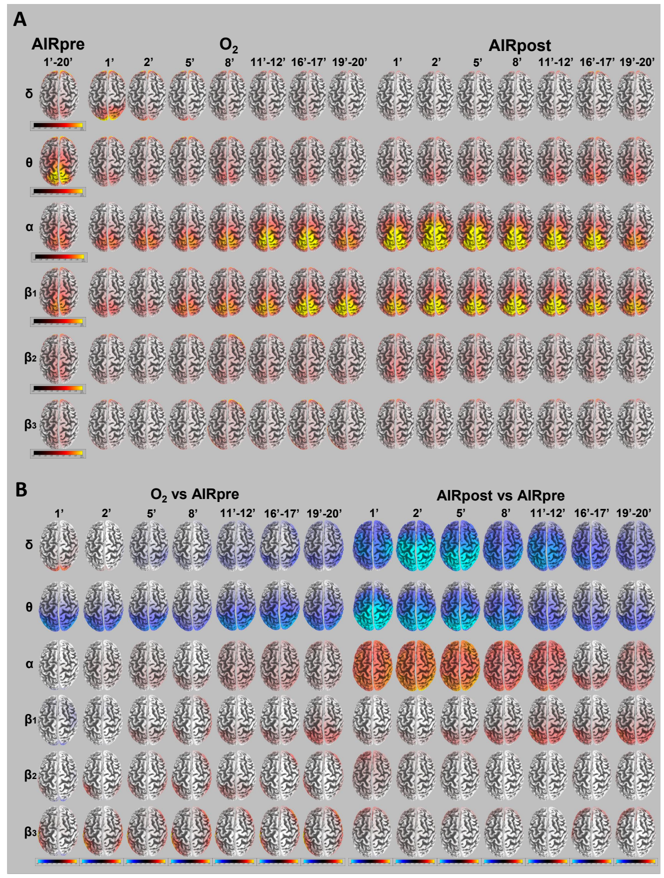

Fig. 2. (A) Averaged sLORETA solutions of EEG sources for each frequency band and for each condition. (B) sLORETA statistical maps. Colored areas represent the spatial extent of voxels with a significant difference (yellow and light blue-coded for $p < 0.05$, corrected for multiple testing) in source current density in O_2 vs. AIRpre and AIRpost vs. AIRpre.

the first 2 mins after decompression before returning almost completely to baseline at 19'−20' (Figure2B).

3.2. Brain connectivity

In the baseline (AIRpre) significant and strong connections between Fz and parietal electrodes were observed in all frequency ranges. In the O_2 breathing condition, the brain connectivity increased from frontal to posterior regions at 5', 11'-12', 16'-17' and 19'-20', principally in alpha, beta1 and beta2 bands as compared to the early minutes of O_2 breathing. At minute 8 few and weaker connections were observed (Figure3). After decompression (AIRpost), few connections were observed until minute 5. Connections between the same regions (from frontal to posterior) revealed a significant increase in their strength at 5', in alpha, beta1, beta2, and beta3. After 20 mins the connectivity pattern resembled that of AIRpre even if it did not completely return to the baseline.

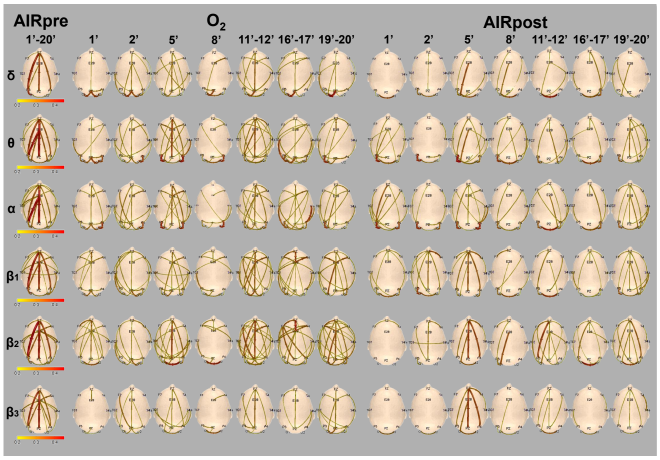

Fig. 3. Averaged connectivity pattern obtained for AIRpre, O_2 and AIRpost in all frequency ranges. Functional connections are expressed with arrows conneting one channel (the source) to another one (the target).

4. CONCLUSIONS

One of the main technical results obtained in this study is that the EEG signal quality recorded in hyperbaric chamber with Bluetooth technology is better than with older ones because the transmission of the amplified signals is less subject to environmental interference and because it enables wireless connection without cables which can generate eddy currents.

Rarely, EEG signal has been used for the evaluation of brain activity during hyperoxia in hyperbaric chamber. Visser et al. [7] described the effects of hyperbaric oxygen (HBO) exposure on quantitative EEG and noted that the electrical changes were minor and not considered indicative of a HBO effect on the brain in the group of healthy subjects who showed no signs of toxicity.

This study is the first to investigate the brain functional networks in EEG recordings in professional divers under simulated deep-sea condition. The principal results of EEG recording in the three different conditions showed that cortical sources and the connectivity pattern are affected by O_2 breathing for at least 20 mins. The oxygen condition was characterized by a marked amplitude increase in the alpha and beta1 sources in the parietal and occipital areas and an amplitude decrease in the occipital delta and theta sources, with a parallel disconnection of the frontal-parietal links in the early minutes of O_2 breathing. Our results support the hypothesis that the prolonged hyperoxia in these healthy subjects induced vasoconstriction followed by vasodilatation, with an increase in alpha activity in the posterior regions, increase of occipital connections and decrease of frontal-parietal connections.

During the selection of military divers, an oxygen tolerance test (OTT) can be used to identify subjects with susceptibility to CNS O_2T [8]. The Italian Navy OTT procedure involves exposing divers to 2.8 ATA (oxygen toxicity can occur above 1.8 ATA) for 15 mins in a dry chamber breathing 100% O_2 through a face mask. As described by our findings, the EEG can significantly change during saturation dives and support the OTT and the evaluation of subjects with susceptibility to CNS O_2T. The EEG biomarkers, such as abnormal electrical source localization or connectivity patterns, would provide a non-invasive tool to predict dangerous operational situations of professional divers.

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