Marcin KOŁODZIEJ[1], Krzysztof KOWALCZUK[2], Andrzej MAJKOWSKI[1], Paweł TARNOWSKI[1], Stefan GAŹDZIŃSKI[2], Remigiusz Jan RAK[1]

Warsaw University of Technology (1), Military Institute of Aviation Medicine (2),

doi:10.15199/48.2020.01.27

Analysis of artefacts in EEG signal registered during anti-G straining maneuvers

***Abstract**. An anti-G straining maneuver (AGSM) is an essential element of training pilots of high-maneuver aircrafts. Electroencephalographic signal (EEG) registered during such maneuvers could be used to detect cerebral ischemia. AGSM involves complicated physical tasks, from stretching certain parts of muscles through adequate breathing. This results in the creation of extremely large muscle artefacts, which significantly disrupt the recorded EEG signals. The presented research concerned EEG signals, recorded during individual AGSM phases, inside an overload centrifuge. The largest artefacts in the EEG band (0.5-300Hz) were observed for the electrodes Fp1, F9, FT9 and EMG1 located on cheek. The signal from the Cz and Pz electrodes appeared to be the least disturbed.*

***Streszczenie.** Manewr przeciw-przeciążeniowy (AGSM) jest niezbędnym elementem szkolenia pilotów samolotów wysokomanewrowych. Sygnał elektroencefalograficzny (EEG) zarejestrowany podczas tych manewrów mógłby posłużyć do wykrycia niedokrwienia mózgu. Manewr przeciw-przeciążeniowy, obejmuje skomplikowane zadania fizyczne, od napinania pewnych partii mięśni, poprzez odpowiednie oddychanie. Powoduje to powstanie ekstremalnie dużych artefaktów odmięśniowych, które zakłócają, w sposób znaczący, rejestrowane sygnały EEG. Zaprezentowane badania dotyczyły sygnałów EEG zarejestrowanych podczas wykonywania poszczególnych faz AGSM, we wnętrzu wirówki przeciążeniowej. Największe artefakty w paśmie EEG (0.5-300Hz) zaobserwowano dla elektrod Fp1, F9, FT9 oraz EMG1 ulokowanej na policzku. Najmniej zakłócony okazał się sygnał zarejestrowany z elektrod Cz i Pz. (**Analiza artefaktów w sygnale EEG zarejestrowanym w trakcie wykonywania manewru przeciw-przeciążeniowego**)*

Keywords: anti-G straining maneuver (AGSM), electroencephalography (EEG), electromyography (EMG), signal analysis, artefact correction.
Słowa kluczowe: manewr przeciw-przeciążeniowy (AGSM), elektroencefalografia (EEG), elektromiografia (EMG), analiza sygnałów, korekcja artefaktów.

Introduction

High-maneuver aircraft can achieve very large and rapidly increasing accelerations. Under these conditions, the supply of oxygen to the brain can be stopped suddenly, and the transition from the state of consciousness to its loss occurs without warning [1]. Pilot's tolerance for acceleration could be increased, among other things, through physical training. In practice, in high accelerations, pilots perform the so-called anti-G straining maneuver (AGSM) [2]. This maneuver consists in the proper coordination of three independent activities: 1) taking the right body position, 2) appropriate breathing, 3) skeletal muscle tensioning [3]. For example, the M-1 maneuver, proposed by Dr. Wood already in 1946, involves taking the right position in the pilot's seat (torso slightly inclined, head tucked between the arms, tensioning the muscles of the whole body) and the use of a special method of breathing, i.e. making vigorous exhalations, repeated every 3-5 seconds, with a partially closed glottis, preceded by a full exhalation in a time not exceeding 1s [4]. To properly train AGSM, a human centrifuge is used, in which accelerations close to real conditions are obtained.

Monitoring the electroencephalographic (EEG) signal could help in the detection, or even prediction, of loss of consciousness (G-LOC) by the pilot [5,6]. It can also be useful for assessing of his psychophysical predispositions or in Brain Computer Interfaces [7,8]. Unfortunately, physical tasks performed during AGSM generate muscle activity, which significantly interferes with the EEG measurement. In addition, EEG signals are registered in technically difficult conditions (many electrical and electronic devices), which cause the appearance of significant technical artefacts [9]. Earlier attempts to remove such artefacts were unsuccessful under high-G acceleration [10]. Registering a useful EEG signal, during increased muscle activity and large technical artefacts is extremely difficult and at the same time extremely desirable.

The aim of the work is to investigate the sources of artefacts, that arise during anti-G straining maneuvers. Investigating what kind of artefacts in the EEG signal are generated during the execution of individual phases of this maneuver, can contribute to a better understanding of the artefact formation process and ultimately contribute to the development of a method for their elimination. We also tried to answer the question from which electrodes the recorded EEG signals are least disturbed. An attempt was also made to analyze artefacts using ICA and to eliminate them using regression methods [11].

Methods

Electroencephalographic and electromyographic (EEG and EMG) signals were recorded for the purposes of the tests, while performing anti-G straining maneuvers. The maneuvers were performed by an aviation instructor with many years of experience in the centrifuge at the Aeromedical Training Department of Military Institute of Aviation Medicine in Warsaw, Poland [12]. Training in the centrifuge allows to reproduce and maintain the overloads. Additionally, performing the experiment in the centrifuge, allowed to record all potential artifacts that will have to be dealt with during future EEG studies under high-G accelerations. The costs of centrifuge training are disproportionately lower than the possible costs of a modern combat aircraft. The centrifuge gondola, installed on an 8-meter-long arm, makes it possible to achieve overload in the "Z" axis in the range from -3G to 16G with the maximum gradient of overload growth 14.5 G/s. In addition, gyroscope suspension of the gondola assures setting of overloads, also in the X and Y axes, in the range of ± 10G and ± 6G, respectively. The simulator is designed for training cadets, pilots of high-maneuver planes (combat, aerobatic and sport).

During the experiments, the centrifuge had all electronic, electrical and pneumatic equipment turned on. A g.USBamp amplifier from g.Tec and OpenVIBE software were used to record EEG/EMG signals. Signals were recorded at the sampling frequency *fs*=1200Hz. A bandpass (0.01-500Hz) digital filter and a 50Hz narrow-band filter were used. During the tests eight EEG signals were recorded: Cz, C3, P7, C4, Pz, Fp1, F9, FT9 and two EMG signals: EMG1 -

electrode located on the left cheek, EMG2 - electrode located on the left side of the neck.

The first, reference task (Z1) consisted of calm natural breathing. The next four tasks (Z2–Z5) consisted of executing individual phases of the AGSM. Physical tasks (components of the maneuver) and their descriptions are presented in Table 1.

Table 1. Description of tasks

Task	Description
Z1	Calm natural breaths (baseline)
Z2	Muscle component, tightening the muscles of the lower part of the body
Z3	Respiratory component, increasing the pressure in the chest without quick inhalations and exhalations
Z4	Respiratory component, rapid inhalation and exhalation
Z5	Full anti-G straining maneuver

Preprocessing

To assess the recorded EEG/EMG signals in the frequency domain, spectral analysis was performed using the FFT algorithm. This assessment indicated the presence of significant technical artefacts, inside the overload centrifuge. The spectrum of the recorded EEG signal from the Cz electrode is shown in Fig. 1.

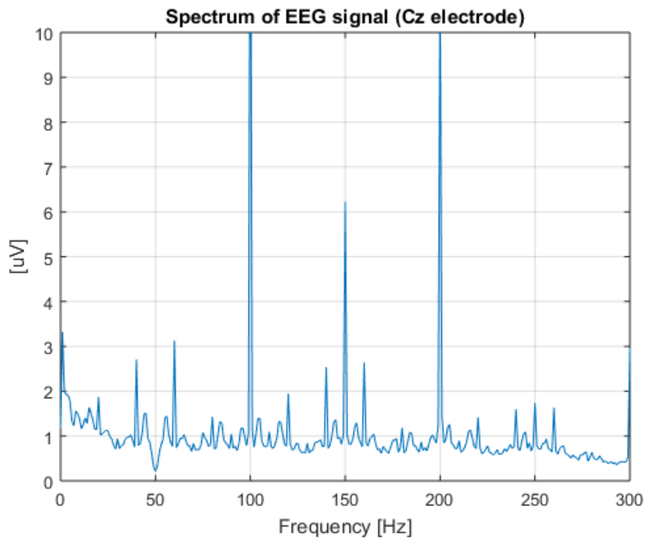

Fig.1. The EEG signal spectrum recorded on the electrode Cz

In Fig. 1, the entire spectrum of harmonics related to mains frequency (100, 150, 200, 250 Hz) and other frequencies produced by electronic devices (40, 60, 120, 140, 160 Hz) can be observed. This shows significant technical artefacts of an unknown origin. To get rid of technical artefacts and other distortions, we decided to use Common Average Reference (CAR) filter [13]. The CAR method removes common interferences. In principle, the technical artefacts are the same on all electrodes. The EEG signal spectrum after applying CAR filter for the Cz electrode is shown in Fig. 2. We can observe a significant decrease in the power of technical artefacts.

Because the CAR filter, did not completely eliminate technical artefacts, we decided to use narrowband digital filters to eliminate the remains of artefacts from electrical devices for harmonics (100, 150, 200, 250Hz). An example of 4 seconds window of the EEG signal after removing technical artefacts is presented in Fig. 3.

In Fig. 3, however, we can observe physiological artefacts associated with normal activities: blinking (Fp1), eye movements (F9), heart activity (EMG2).

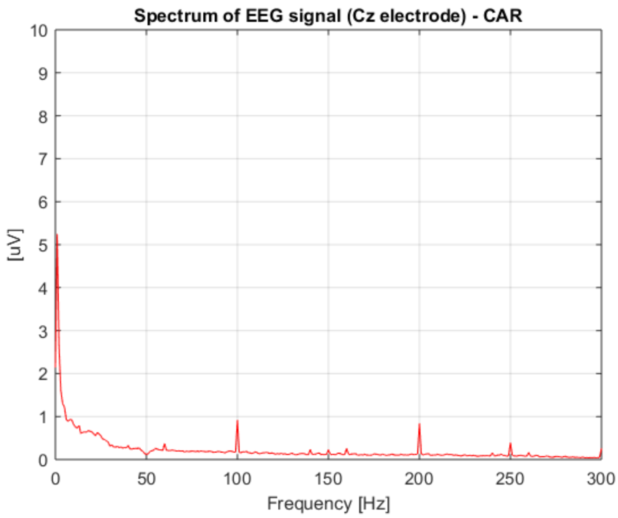

Fig.2. The EEG signal spectrum recorded on the Cz electrode after applying CAR filter

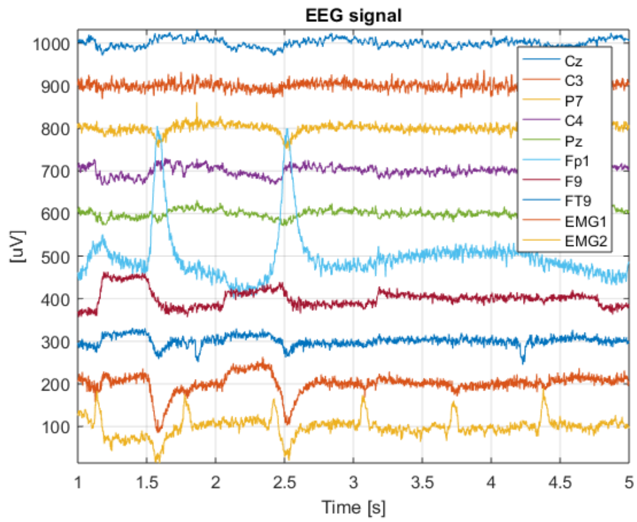

Fig.3. Example of 4 seconds of EEG signal after removal of technical artefacts

Analysis

An example of registered EEG signals during a full anti-G straining maneuver (Z5) is shown in Fig. 4. We can observe a significant increase in artefacts related to muscle tightening (higher frequencies) and slow-changing waves associated with breathing (movement of the electrodes). In order to assess which phases of the maneuver induce the largest artefacts, calculations of the signal energy were done. For this purpose, the EEG signal for individual phases of AGSM was divided into time windows of length *N=fs/4* samples. For each electrode and time window, the signal energy in bands: alpha (8-12Hz), beta (12-32Hz), gamma (32-100Hz), delta (0-4Hz), theta (4-8Hz) and the entire EEG band (0.5-300Hz) were calculated. The results of the average energy values for delta, gamma and the entire EEG band for individual electrodes are presented in Tables 2–4.

For the entire EEG band and the Z1 task (calm natural breaths) we can observe the highest energy values for the Fp1 (1156.7 uV^2), the EMG1 (169.4 uV^2) and EMG2 (272.0 uV^2) electrodes (Table 2). The relatively high signal energy for the Fp1 electrode is due to the electrical potentials associated with closing/opening the eyes (blinking). The EMG1 electrode (located on the cheek) also contains blinking potentials. In contrast, the EMG2 electrode (located on the neck) contains components associated with the work of the heart.

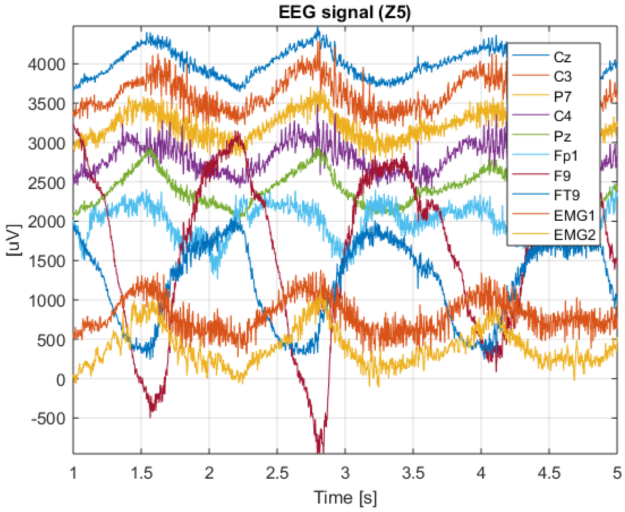

Fig.4. An example of a registered EEG signal during a full anti-G straining maneuver (Z5)

Table 2. The signal energy [uV^2] in the EEG band (0.5-300 Hz) during performing individual tasks of AGSM

Electrode	Z1	Z2	Z3	Z4	Z5
Cz	32,9	39,2	37,4	793,4	3876,2
C3	63,8	85,7	65,2	3092,4	7944,6
P7	52,1	182,3	64,9	1368,1	6438,1
C4	49,2	84,9	44,2	6035,5	6941,6
Pz	35,7	49,9	30,2	597,1	5525,3
Fp1	1165,7	938,5	57,9	3402,9	12907,5
F9	94,8	83,5	33,0	1200,6	95093,3
FT9	65,7	63,6	40,1	1662,8	35709,1
EMG1	169,4	235,4	57,7	1380,2	11275,0
EMG2	272,0	393,6	293,7	3295,1	9899,7

Table 3. The signal energy [uV^2] in the delta band (0-4 Hz) during performing individual tasks of AGSM

Electrode	Z1	Z2	Z3	Z4	Z5
Cz	1493,2	1687,7	2713,2	2849,2	4519,6
C3	26,1	19,3	12,4	239,6	3788,0
P7	511,3	586,6	578,3	128,4	2803,1
C4	654,6	560,0	451,3	346,0	2909,9
Pz	459,5	665,6	1236,9	855,3	5157,3
Fp1	1123,8	1000,5	404,8	3579,7	10425,7
F9	1043,1	1368,4	1930,4	1498,1	96577,0
FT9	1423,0	1685,7	2360,7	1575,7	34882,5
EMG1	10526,9	12373,7	17578,2	9988,2	11633,0
EMG2	12479,6	15049,6	20365,4	12352,2	20077,3

Table 4. The signal energy [uV^2] in the gamma band (32-100 Hz) during performing individual tasks of AGSM

Electrode	Z1	Z2	Z3	Z4	Z5
Cz	3,4	6,5	3,9	289,0	405,9
C3	24,6	27,7	20,8	1355,5	2277,6
P7	9,6	40,7	18,2	414,8	1335,5
C4	6,4	21,3	10,7	2735,4	2157,9
Pz	4,3	7,7	4,2	191,1	333,8
Fp1	28,3	27,0	7,7	431,5	1833,1
F9	7,2	10,9	4,6	459,2	939,3
FT9	9,1	11,8	6,6	598,5	954,1
EMG1	9,2	36,1	5,9	420,6	3875,6
EMG2	11,2	40,2	25,5	955,7	1057,6

The average energy values in the EEG band for all electrodes and for individual tasks Z1–Z5 were respectively: 200,1 uV^2, 215,6 uV^2, 72,4 uV^2, 2282,8 uV^2, 19561 uV^2. Thus, the largest increase in the value of artefacts occurred for tasks Z4 and Z5. No significant energy changes were observed for tasks Z2–Z3 in relation to the task Z1 (baseline).

The average energy values in the delta band (0–4Hz) for tasks Z1–Z5 were respectively: 2974,1 uV^2, 3499,7 uV^2, 4763,1 uV^2, 3341,2 uV^2, 19277,3 uV^2 (Table 3). The largest increase in the value of artefacts, caused by the movement of the electrodes, occurred for the Z5 task. No significant energy changes were observed for tasks Z2–Z4. The largest drift can be observed for the electrodes Fp1, F9, FT9, EMG1 and EMG2. These electrodes are located in the areas of the temple, forehead, cheek and neck. On the other hand, the smallest increase in energy (smallest artefacts) was observed for the electrodes C3, C4, Cz, P7 and Pz.

The average energy values in the gamma band (32–100Hz) for tasks Z1–Z5 were respectively: 11,33 uV^2, 22,99 uV^2, 10,81 uV^2, 785,13 uV^2, 1517,04 uV^2 (Table 4). Thus, the largest increase in the value of artefacts caused by muscle activity occurred for the Z4 and Z5 task. No significant energy changes were observed for tasks Z2–Z4.

Discussion

Recorded EEG signals for full AGSM in the gamma band (32–100Hz) along with the signal of muscle activity are presented in Fig. 5. A high energy can be observed on the electrodes: EMG1 (3875,6 uV^2), EMG2 (1057,6 uV^2), C3 (2277,6 uV^2), C4 (2157,9 uV^2), Fp1 (1833,1 uV^2) and P7 (1335,5 uV^2).

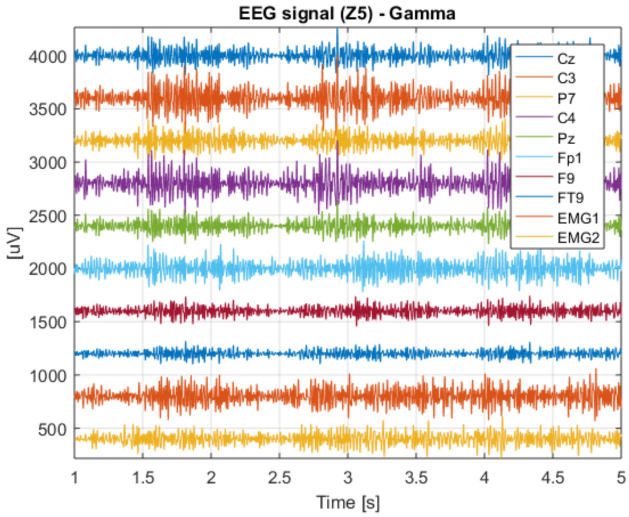

Fig.5. Recorded EEG signals for full AGSM in the gamma band (32–100Hz) associated with muscle activity

The smallest muscle artefacts were observed on the Cz (405.9 uV^2) and Pz (333,8 uV^2) electrodes. Muscle artefacts on the Cz and Pz electrodes were about five times smaller than on the C3 and C4 electrodes but still more than 110 times stronger than the EEG signal in the gamma band.

We also calculated the Pearson correlation coefficient between the energy in the gamma band (muscle activity) and the energy in the alpha, beta, theta, delta bands, for the Cz electrode (the least disturbed by artefacts). The values of the coefficient were respectively 0.014 for the alpha band, 0.708 for the beta band, -0.012 for theta band and 0.004 for the delta band. This indicates a strong correlation of artefacts with the beta band and weak correlation with the alpha, theta and delta bands.

Figure 6 presents signal spectra for the Cz, Fp1, EMG1 and EMG2 electrodes. The largest amplitudes of 30–150Hz frequency components, can be observed on the EMG1 electrode, slightly smaller on the Fp1 electrode. Thus, the muscle activity associated with flexing chick muscles (EMG1) seems to be the source of artefacts during the rapid exhalation of air.

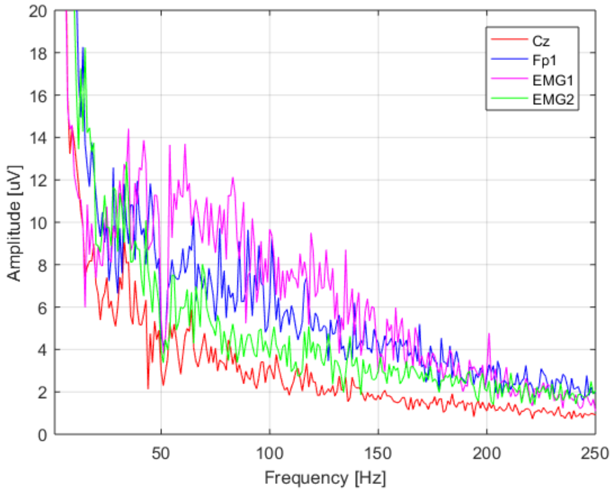

Fig.6. Spectra of registered EEG/EMG signals

Muscle artefacts were also generated near the forehead (Fp1 electrode). Smaller amplitudes of frequency components from the range 30–150 Hz can be observed on the EMG2 electrode (neck). However, it does not mean that some of these components do not transfer to other EEG signals, for example a Cz electrode.

Independent component analysis (ICA) is used to analyze the sources of artefacts and EEG signals [14,15]. We used the *runica* algorithm for 10 registered electrophysiological signals to calculate ICA components. The results of the decomposition are presented in Fig. 8 along with exemplary weight distribution for components. The drawings represent the weights from which the components were calculated. The red color depicts the large value of the component, the blue color - the small value. The second component is associated with artefacts, generated as a result of muscle tightening and the movement of the F9 electrode. The third component is associated with signals generated just above the surface of the eye. The eighth component is associated with the signals generated during the rapid exhalation of air. The tenth component is associated with pulse.

As the result of ICA analysis, it was not possible to obtain a component containing pure EEG signal. We can assume that it could be the component number 6, but still we have no guarantee that it is associated only with EEG signal. The ICA analysis allows to obtain maximum of 10 independent components (as many as the input signals) but it seems that the number of artefact sources probably exceeded 10. In future, one would be tempted to use more electrodes but this could be difficult to apply in practice.

We can observe an amplitude reduction of the corrected signals (Cz I and Cz II). It seems, therefore, that the method removed signals associated with muscle artefacts. However, it is still uncertain whether the signal received is a clear EEG signal. In order to perform detailed tests of the artefact correction method, EEG signals containing potentials with known morphology should be recorded in the future. This would make it easier to evaluate the effectiveness of the EEG artefact correction method.

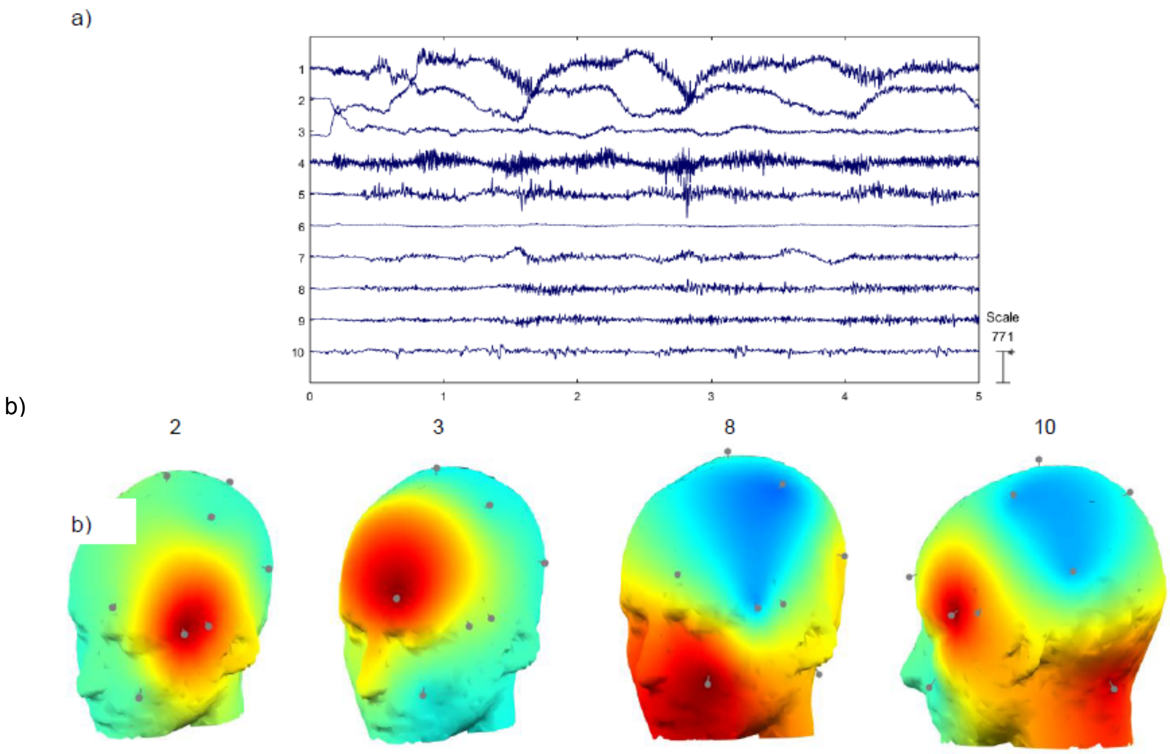

Fig. 7 Decomposition of registered EEG/EMG signals to ICA components (a), weights for 2nd, 3rd, 8th and 10th ICA component (b)

An attempt was also made to remove muscle artefacts from the Cz electrode. For this purpose, the regression method was used, which consisted in subtracting from the electrode Cz the muscle artefacts. It was assumed that muscle artefacts were recorded on electrodes: EMG1, EMG2, Fp1, F9. Artefact signals have been subtracted (with certain weights) from the Cz electrode, so as to minimize the established cost function. Two variants of the objective function were used: I) minimization of variance, II) minimization of the sum of correlation coefficients between the Cz electrode and artefacts registered on EMG1, EMG2, Fp1, F9 electrodes. Weight values were calculated for every possible combination of electrodes and next we chose those that minimized cost function. The fragment of the signal Cz (without correction) and the signal after correction using the first (Cz I) and the second (Cz II) methods is presented in Fig. 8.

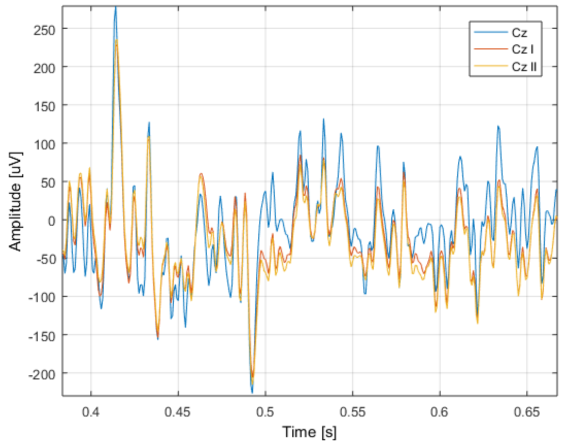

Fig. 8. Fragment of signal Cz (without correction) and the signal after correction using the first (Cz I) and the second (Cz II) method

Conclusion

A significant occurrence of artefacts associated with performing an anti-G straining maneuver (AGSM) was observed. The largest artefacts that interfere with the EEG signal, arise during the phase associated with rapid inhalations and air exhalations. The largest artefacts in the EEG band (0.5-300Hz) were observed for the electrodes Fp1, F9, FT9, EMG1 (cheek). The signal from the Cz and Pz electrodes appeared to be the least disturbed.

The AGSM makes it difficult to interpret EEG signals. In order to clean the EEG signals from artefacts, it is possible to use known techniques such as ICA or regression method. In the future, EEG signals containing potentials with known morphology should be recorded in order to check the effectiveness of removing artefacts.

***Authors**: dr inż. Marcin Kołodziej, dr inż. Andrzej Majkowski, mgr inż. Paweł Tarnowski, prof. dr hab. inż. Remigiusz Jan Rak, Warsaw University of Technology, Institute of Theory of Electrical Engineering, Measurement and Information Systems, ul. Koszykowa 75, 00-662 Warsaw, E-mail: marcin.kolodziej@ee.pw.edu.pl; płk rez. dr n. med. Krzysztof Paweł Kowalczuk, dr hab. n. med. Stefan Gaździński, Military Institute of Aviation Medicine, ul. Krasińskiego 54/56, 01-755 Warsaw.*

REFERENCES

[1] Yilmaz, U., Visual Symptoms and G-LOC in the Operational Environment and During Centrifuge Training of Turkish Jet Pilots, 70, (1999), 4.
[2] Sevilla, N. L., and Gardner, J. W., G-Induced Loss of Consciousness: Case-Control Study of 78 G-LOCs in the F-15, F-16, and A-10, *Aviation, Space, and Environmental Medicine* 76, (2005).
[3] Lyons, T. J., Marlowe, B. L., Michaud, V. J., and McGowan, D. J., Assessment of the anti-G straining maneuver (AGSM) skill performance and reinforcement program, *Aviat Space Environ Med* 68, (1997), 322–324.
[4] Whinnery, J. E., and Gondek, M. R., Medical evaluation of G-sensitive aircrewmen, *Aviat Space Environ Med* 49, (1978), 1009–1013.
[5] Lukatch, H. S., Echon, R. M., MacIver, M. B., and Werchan, P. M., G-force induced alterations in rat EEG activity: a quantitative analysis, *Electroencephalography and Clinical Neurophysiology* 103, (1997), 563–573.
[6] Sawicki, D., Wolska, A., Roslon, P., and Ordysinski, S., New EEG Measure of the Alertness Analyzed by Emotiv EPOC in a Real Working Environment, in *NEUROTECHNIX*, 2016).
[7] Majkowski, A., Kolodziej, M., and Rak, R. J., Implementation of selected EEG signal processing algorithms in asynchronous BCI, *IEEE International Symposium on Medical Measurements and Applications Proceedings*, (2012), pp. 1–3.
[8] Li, Y., Zhang, T., Wang, B., and Nakamura, M., EEG and related physiological signals investigation under the condition of +Gz accelerations, *ICME International Conference on Complex Medical Engineering (CME)*, (2012), pp. 60–65.
[9] Li, Y., Zhang, T., Deng, L., and Wang, B., Acquisition technology research of EEG and related physiological signals under +Gz acceleration, *Ir J Med Sci* 183, (2014), 187–197.
[10] Kowalczuk, K., Strojek, M., and Walerjan, P., Recording EEG Data in Human Centrifuge Conditions – Preliminary Report, *PJAMBP* 21, (2015).
[11] Gwin, J. T., Gramann, K., Makeig, S., and Ferris, D. P., Removal of Movement Artifact From High-Density EEG Recorded During Walking and Running, *Journal of Neurophysiology* 103, (2010), 3526–3534.
[12] Human Training Centrifuge, [Online], available at: http://www.wiml.waw.pl/?q=en/Dynamic_Flight_Simulator .
[13] McFarland, D. J., McCane, L. M., David, S. V., and Wolpaw, J. R., Spatial filter selection for EEG-based communication, *Electroencephalography and Clinical Neurophysiology* 103, (1997), 386–394.
[14] Mennes, M., Wouters, H., Vanrumste, B., Lagae, L., and Stiers, P., Validation of ICA as a tool to remove eye movement artifacts from EEG/ERP, *Psychophysiology* 47, (2010), 1142–1150.
[15] Winkler, I., Debener, S., Müller, K., and Tangermann, M., On the influence of high-pass filtering on ICA-based artifact reduction in EEG-ERP, *37th Annual International* Conference *of the IEEE Engineering in Medicine and Biology Society (EMBC)*, (2015), pp. 4101–4105.