

Personal EEG monitoring device with electrode validation

The present invention relates to the measurement of EEG signals. The invention more particularly relates to a personal wearable EEG monitor adapted to be carried at the head of a person. The EEG monitor comprises an EEG sensor part having electrodes arranged on the skin surfaces of a person for measuring one or more EEG signals from said person. The EEG monitor further comprises an EEG signal analyzer adapted for having an EEG signal transferred from the EEG sensor part, and adapted for monitoring the EEG signal from the person wearing the device.

Personal wearable EEG monitors are known for surveillance of EEG in order to detect eminent seizures, but could also be applied for long term EEG recording.

Such personal wearable EEG monitors are known from WO 2007/150003 describing a system for long term EEG monitoring with implanted electrodes. WO 2006/066577 describes a personal monitoring device for detecting the onset of hypoglycemia by analyzing an EEG signal obtained through implanted electrodes. WO 2007/047667 describes EEG monitoring partly by application of an electrode in the ear canal. The application of auditory evoked potentials is also described.

It has been found that wearable personal devices for long term measurements of EEG-signals can be located in the region behind or in the ear of the user with several advantages. This location is ideal for physiologic, cosmetical and mechanical reasons. Also, a measurement of the EEG signal in the ear canal has the advantage of being better protected against external electrical fields since the ear canal extends into the head which will shield the EEG electrodes partly. It is possible to obtain a very good fit between an earpiece holding the electrode and the ear canal, and thereby the contact between the skin and the electrode becomes less sensitive to movements and skin strain. Further to this the ear itself, or part of it, may be used for attachment of the device. Many EEG signals are also available from the ear region.

Other examples of wearable EEG monitors could be hearing aids with EEG-feedback (e.g. the hearing aid is in some way adjusted according to information extracted from an EEG signal) and personal health monitoring devices. Examples of personal health monitoring devices could be hypoglycemia warning devices for persons with diabetes
5 and seizure warning devices for persons with epilepsy. Also continuous monitoring of the EEG signal for diagnostic or research purposes may be relevant.

The requirements and trade-offs between different characteristics for electrodes for EEG measurements in wearable personal devices are different from those for electrodes
10 for clinical use, e.g. short term EEG monitoring of a patient in a hospital. Typical requirements for electrodes in wearable personal devices are, that they must be easy to put in place, they should not exert any stress on the skin (e.g. no strain of the skin), they must be comfortable and small (e.g. the size of a hearing aid), they must be cosmetically acceptable, addition of gel between skin and electrode should be avoided
15 (i.e. dry electrodes), and in general no skin preparation should be necessary. These requirements compromise the signal acquisition properties and the reliability of the electrodes, as the requirements will make it more difficult to obtain a good electrical contact between skin and electrode. Thus electrodes designed for such devices have typically much larger impedances (e.g. in the hundreds of kilo Ohm range), larger
20 variations in impedances, and are less reliable than electrodes for clinical use.

Traditionally electrodes for electrical bio-potential measurements, such as EEG, are validated by measuring the electrical impedance between two or more electrode elements. This method is feasible for clinical use and for electrodes with reasonably
25 low impedances, e.g. less than a few hundred kilo Ohms. Measurement of electrical impedance has now been found not to be sufficiently reliable for electrodes with very large electrical impedance. This is because measuring the electrical impedance will only reveal if there is an electrical connection between two electrodes, but not if the electrodes are measuring an EEG signal. The electrical connection can also be achieved
30 by a layer of dirt on the part holding the electrodes.

In long term measurements of EEG-signals in wearable personal devices there is a need for validating the EEG signal measured by the electrode, and for the reasons mentioned above there is a need for an alternative method to the electrical impedance method. The electrode validation must be easily performed by the user. Furthermore the electrode
5 validation should preferably be an integrated capability of the device.

The solution has been found in the form of a personal wearable EEG monitor further comprising EEG stimuli controlling means adapted for performing at least one of the following:

- 10 - providing a stimulus to said person,
- request said person to perform a stimulus creating act,
- identifying a potentially stimulus-creating ambient sound.

The EEG monitor further comprises EEG response detection means for identifying an induced response from the EEG signal caused by said stimulus, and a classifier for
15 deciding based on said at least one induced response if said skin surface electrodes receive EEG signals of said person.

The term induced response refers to an EEG signal induced by a stimulus which is distinct from the otherwise spontaneous EEG signal. Examples of induced responses
20 are listed in Table 1 below. One possible stimulus considered in the system described here is an auditory stimulus in a broad sense, and the measured signal could e.g. be an auditory evoked response.

Auditory evoked potentials can be used to trace the signal generated by a sound
25 through the ascending auditory pathway. Thus the measured signal may include induced responses generated in the cochlea, the cochlear nerve, the cochlear nucleus, the superior olivary complex, the lateral lemniscus, the inferior colliculus in the midbrain, the medial geniculate body, or from the cortex. Thus an induced auditory response may reflect:

- 30 1) A direct and autonomous response to the acoustical signal in the processing of the stimulus in the auditory pathway;

- 2) A response caused by processing in the cortexes of the brain.

Whereas the first, referred to as an auditory evoked potential, is an innate response from the auditory pathway processing, the latter may require cooperation or certain
5 acquired skills by the user.

To exploit induced responses of the first kind the acoustical signal typically has certain simple acoustical characteristic such as e.g. an amplitude modulation or a pitch sweep.

- 10 To exploit induced responses of the second kind the signal typically has more complex information such as e.g. a series of syllables, words or even sentences containing instructions or sentences with syntactical errors.

The methodology of auditory evoked responses is well known in e.g. the area of
15 research of the auditory pathways and in medicine for diagnostic use. Below the use of induced responses for electrode validation is described with focus on a setup where a certain response is expected, and the presence of the expected response validates that the electrodes are measuring valid EEG signals.

- 20 The EEG sensor part is to be understood as the combined EEG electrodes whether these are placed together in a unit or connected only by wires. The EEG sensor part may or may not include signal acquisition means for collecting and preprocessing the EEG signal from the electrodes. If no induced response can be detected in the EEG signal, the reason may be that there is no, or a very bad, electrical connection between
25 one or more electrodes and the skin surface. In that case a notification may be given in order for the person to rearrange the electrode.

The potentially stimulus-creating ambient sound could e.g. be a sudden sound after a period of relative silence. It could also be other sudden changes in the background
30 sounds. The term potentially refers to that there is no certainty that a sound identified also induces an EEG response.

According to a first aspect of the invention, there is provided a personal wearable EEG monitor adapted to be carried at the head of a person, said EEG monitor comprising EEG sensor part having skin surface electrodes for measuring one or more EEG signals from said person, wherein at least one electrode is adapted to be arranged in an ear

5 canal of said person; EEG signal analyzer adapted for having an EEG signal transferred from said EEG sensor part, and adapted for monitoring the EEG signal from said person, EEG stimuli controlling means adapted for performing at least one of the following: providing an auditory stimulus to said person from an auditory stimulus means in the ear canal of said person, requesting said person to perform a stimulus-

10 creating act, identifying a potentially stimulus-creating ambient sound, EEG response detection means for identifying an induced response from the EEG signal caused by said stimulus, and a classifier for deciding based on said at least one induced response if said skin surface electrodes receive EEG signals of said person.

In an embodiment of the EEG monitor the electrodes are dry electrodes, i.e. adapted to function without skin preparation, such as a gel between the electrode and the skin. Dry electrodes will have relatively higher impedance and the validation of the electrodes, i.e. confirming that the electrodes actually receive an EEG signal therefore becomes
5 particularly important.

In an embodiment of the EEG monitor at least one electrode is adapted to be removable and arranged in an ear canal of said person. As outlined above the ear canal has several advantages for the measurement of an EEG signal. In a further embodiment two or
10 more electrodes are arranged in the ear canal. An EEG monitor with at least one electrode in both ear canals of a person is also possible.

In an embodiment of the EEG monitor the EEG stimuli controlling means provides auditory stimuli to said person through a receiver or speaker in the monitor. This has
15 the advantage that the person does not need to perform an active act in order to have a validation of the electrodes.

In an embodiment of the EEG monitor the EEG stimuli controlling means are adapted for identifying sounds from the surroundings capable of causing an induced response.
20 This has the further advantage that the person will not even notice that the EEG electrodes are being validated.

In an embodiment of the EEG monitor the EEG stimuli controlling means are adapted for requesting said person to open and close the eyes. This will provide a very clear
25 induced response.

The three different embodiments described for providing the EEG stimuli may be combined, such that e.g. the embodiment with opening and closing the eyes is applied when the electrodes have been arranged or rearranged on the person, and the
30 embodiment identifying sounds from the surroundings is applied for controlling that the electrodes receive the actual EEG signal at regular intervals. If the person is in a silent

acoustic environment, the EEG monitor may apply the embodiment where auditory stimuli are provided.

5 In an embodiment of the EEG monitor the stimulus is repeated at least two times for a validation of the electrodes. This will offer more reliability in the result.

10 In an embodiment of the EEG monitor at least one electrode adapted to be arranged in the ear canal is arranged on an ear-piece, said ear-piece being provided with a permanent shape fitting the ear canal of said person. Such an ear-piece made especially to the dimensions of the ear canal of the person to wear the EEG monitor will make it easy for the person to arrange the ear-piece in exactly the same position every time it is used. This ensures that the EEG signal is obtained from the same position every time the monitor is used. Thereby the EEG signals obtained in one time period will be comparable with EEG signals obtained in a different time period where the ear-piece
15 has been removed and re-arranged between the two time periods. Providing the ear-piece with a permanent shape also includes resilient materials making the ear-piece more comfortable to wear.

20 In an embodiment of the EEG monitor the monitor comprises a pad electrode arranged external to the EEG sensor part, where the pad electrode is adapted to be arranged on the head of the person to be monitored. Such a pad electrode can be used for special purposes such as obtaining specific EEG signals not available from the ear canal.

25 In an embodiment of the EEG monitor the monitor is adapted for testing the validity of the electrodes as a group. In an alternative embodiment the validity of the electrodes is tested pair wise. If all possible combinations of electrodes are tested pair wise, the validity of each individual electrode can be clarified.

30 In an embodiment of the EEG monitor the validation of electrodes by identifying induced response is combined with measuring the electrical impedance between electrodes placed on the skin surface. This may also increase the reliability of the electrode validation.

In an embodiment the EEG monitor further comprises notification means for notifying said person if the EEG signal is not received. The person may then improve the positioning of the electrode part. In a further embodiment the EEG monitor comprises means for transmitting a wireless notification to an external unit in the event that the
5 EEG signal is not received by the electrodes.

According to a second aspect of the invention, there is provided a method for continuously monitoring EEG signals of a person by an EEG monitor carried at the head of said person, said method comprising the steps of measuring one or more EEG
10 signals from said person by an EEG sensor part having skin surface electrodes, wherein at least one electrode is adapted to be arranged in an ear canal of said person, transferring an EEG signal from said EEG sensor part to a processing unit having EEG signal processing means, monitoring the EEG signal from said person in said processing unit, causing an induced response in the EEG signal by performing at least
15 one of the following: providing an auditory stimulus to said person from an auditory stimulus means in the ear canal of said person, request said person to perform a stimulus creating act, identifying a stimulus creating ambient sound, identifying an induced response from the EEG signal caused by said stimuli, and deciding based on said induced response if said skin surface electrodes receive EEG signals of said
20 person.

There is also provided a method for continuously monitoring EEG signals of a person by an EEG monitor carried at the head of said person, said method comprising the steps of measuring one or more EEG signals from said person by an EEG sensor part having
25 skin surface electrodes, transferring an EEG signal from said EEG sensor part to a processing unit having EEG signal processing means, and monitoring the EEG signal from said person in said processing unit. The method further comprises causing an induced response in the EEG signal by performing at least one of the following: providing a stimulus to said person, requesting said person to perform a stimulus
30 creating act, or identifying a stimulus creating ambient sound. The method further comprises identifying an induced response from the EEG signal caused by said stimuli, deciding based on said induced response if said skin surface electrodes receive EEG signals of said person, and notifying said person if the EEG signals are not received by said electrodes.

In an embodiment the method comprises the step of notifying said person if the EEG signal is not received by said electrodes.

- 5 In an embodiment the method comprises the step of identifying the specific electrodes receiving an EEG signal. Then the EEG signal can be monitored by these electrodes. In a further embodiment the method comprises the step of reconfiguring the EEG monitor to measure the EEG signal by applying electrodes receiving an EEG signal.
- 10 In an embodiment the method comprises repeating the steps of causing an induced response in the EEG signal and identifying an induced response from the EEG signal at time intervals either preselected or adjusted according to previous decisions if said

electrodes receive EEG signal. The urgency of predicting an imminent seizure for the person may also influence the selection of the time interval.

5 Embodiments of the invention will now be explained in further detail with reference to the figures.

Figure 1 illustrates a block diagram of a Wearable Personal Device incorporating an Electrode Validation System based on auditory evoked response caused by an audio stimulus generated by a speaker.

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Figure 2 illustrates the block diagram figure 1, with the change that the audio stimulus is from the users sound environment.

Figure 3 illustrates an example of a device with integrated electrode validation, with electrodes arranged on an ear plug.

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Figure 4 illustrates a further example of a device with integrated electrode validation, with a further pad electrode.

20 Figure 5 illustrates a completely in-the-ear-canal device.

Figure 6 illustrates initial signal analysis of different time periods.

Figure 7 illustrates three different examples of block diagrams for the frequency analysis blocks in figure 6.

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Figure 8 illustrates example of power spectrum for EEG sampled with eyes closed and open, respectively.

30 Figure 9 illustrates a time frequency plot of the signal analyzed in Figure 8.

Figure 10 illustrates the mean values of the frequency components in the alpha band, i.e. the mean value of a subsample of the second axis in figure 9.

Figure 11 illustrates a histogram of the alpha band power of the signal analyzed in
5 Figure 8, i.e. a histogram of the signal in Figure 10.

Figure 12 illustrates a constructed example of a two dimensional classifier.

Figure 1 shows a system for electrode validation and the measurement setup. The
10 dashed box indicates the wearable personal device 1 with the electrode validation system. The device includes a speaker 2 that receives an electrical signal from an audio generator 6 and generates an acoustical signal. The acoustical signal is intended to lead to an induced EEG potential either directly by the sound alone, thereby obtaining an auditory evoked potential, or indirectly by guiding the person to perform an act causing
15 an induced potential in the EEG signal. The device 1 further includes at least two electrodes 3 for measuring the EEG signal from the user's brain 10. The electrode validation system comprises signal acquisition means 4 for acquiring the EEG signal from the electrodes 3. The electrodes 3 form the EEG sensor part. The signal acquisition means 4 could also have been placed as part of the EEG sensor part. The
20 signal is sent to an EEG signal analyzer 5 where the surveillance of the EEG signal is performed. An electrode validation controller 7 compares acquired signals from the electrodes 3 with the timing of acoustical signals given by the audio generator 6 and speaker 2. Based on this the electrode validation controller 7 decides if the signal acquired by the electrodes is an EEG signal. The classifier deciding if the electrodes 3
25 detect an induced response, and thereby receives the EEG signal, is part of the electrode validation controller 7.

The EEG stimuli controlling means corresponds in the embodiment of figure 1 to the audio generator 6. The EEG response detection means are part of the electrode
30 validation controller 7 and identifies induced response in the EEG signal received from the EEG signal analyzer 5. The decision on whether to notify the person wearing the EEG monitor is made in the electrode validation controller 7. The decision can be

based on preselected criteria. Such criteria may be that if a stimulus does not give an induced response in the EEG signal, a notification could be given directly to the person. Otherwise, a test could be performed again e.g. by application of a different type of stimulus.

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The induced potential amplitudes are in general low compared to the spontaneous potential amplitudes and therefore it is usually necessary to time-average the signals from several stimulations. Because the spontaneous EEG signal by definition is independent of the stimulus, time-averaging can be obtained by adding several time frames of the signal synchronized to respective stimuli. The power of the induced response part of the signal increases with 3 dB every time the number of time averages is doubled. I.e. 3 dB can be obtained at two time-averages, 6 dB can be obtained by four averages, and 9 dB can be obtained by eight averages.

15 Examples of EEG induced response schemes suitable for electrode validation are listed in Table 1. Two of the examples in Table 1 are based on so called mismatch negativity (MMN) or oddball paradigm. The MMN or oddball paradigm is a technique used in general to explore event-related potentials (ERP). The event-related potential is elicited by an unexpected change in a sequence of stimuli. For example, a deviant (d) sound with low probability can be mixed among a series of standard (s) sounds with high probability (e.g., s s s s s d s s s s s d s s s . . .). Simple sounds will be applied for this, e.g. a number of “bib” sounds interrupted by a single “bob” sound. Such sequence is called an oddball sequence. The deviant sound can differ from the standard sounds in one or more perceptual features such as pitch, duration, or loudness. The event-related potential can be elicited regardless of whether the subject is paying attention to the sequence or not. During the oddball sequence, a person can be reading or watching a silent subtitled movie, yet still show a clear MMN.

Figure 2 shows a system for electrode validation based on ambient sound environment and the measurement setup for this electrode validation. The dashed box indicates the wearable personal device 1' with the electrode validation system. The device 1' includes a microphone 8' that measures the ambient sound environment, and an audio

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signal analyzer block 9 for identifying sounds in the surroundings which could cause an induced response. The device 1' further includes at least two electrodes 3 for measuring the EEG signal from the user's brain, and an EEG signal analyzer block. The electrode validation system comprises signal acquisition means 4 for acquiring the EEG signal
5 from the electrodes 3. The signal is sent to a signal analyzer 5'. An electrode validation controller 7' compares acquired signals from the electrodes 3 with acoustic signals recorded by the microphone 8', in order to decide if sounds from the surroundings may cause induced responses, and finally decide if the signals acquired by the electrodes 3 are EEG signals.

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The EEG stimuli controlling means corresponds in the embodiment of figure 2 to the audio signal analyzer 9.

Alternatively to generate the audio-stimuli by the device as shown in Figure 1, the
15 electrode validation may be based on the ambient sound-environment as shown in Figure 2. In this system the device measures both the EEG from the user's brain and the ambient sound environment is measured by a microphone integrated in the device. The EEG signal analyzer 5' and the audio signal analyzer 9 blocks may for instance comprise algorithms for envelope-spectrum estimation, and the electrode validation
20 block may comprise algorithms to exploit the dependencies between the EEG-envelope spectrum and the audio-envelope spectrum. An advantage of this system is that the electrode test may be running at all times and without disturbing the users with audio signals.

25 Examples of induced response schemes suitable for electrode validation are given in table 1, where each scheme is described in detail.

Table 1. Examples of induced response schemes

Scheme	Description
Brainstem Auditory-Evoked Potentials (BAEP) or Auditory Steady State Response (ASSR)	In BAEP the stimuli are typically click or tones. Click stimuli can for instance be 8-10 clicks/sec. Tones can be on/off modulated; or for instance a 500, 1000, 2000, or 4000 Hz carrier amplitude modulated (AM) with modulation rate of e.g. 40 - 100 Hz. The modulator signal frequency and harmonics thereof can be detected in the EEG signal.
Harmonic oddball	An oddball sequence comprising harmonic (h) and disharmonic (d) sounds (e.g.: h h h h h h h d h h h h h d h h h h d h h h . . .). An ERP can be detected in the EEG.
Linguistic oddball	Linguistic anomalies or violations of syntactic or semantic rules in the acoustic stimuli cause ERPs. An ERP can be detected in the EEG.
Open/closed eyes	Alpha waves are oscillations in the frequency range of 8 - 12 Hz arising from synchronous and coherent electrical activity of cells in the human brain, see [1]. Alpha waves in EEG predominantly originate from the brain during wakeful relaxation with closed eyes. Thus by instructing the user to "open" or "close" the eyes a simple induced by instruction paradigm is established. This is also known as an Alpha Attenuation Test (AAT).

- 5 Figure 3 shows a sketch of an embodiment of an EEG monitor device. The device is a behind-the-ear style device which is well-known from hearing aids. Typically it comprises a behind the ear part 12 with battery, electronic circuit and a microphone. The device 1 further comprises an ear-piece 15 and a connecting wire 14 between the

behind the ear part 12 and the ear-piece 15. The electrodes are placed on the surface of a custom made ear-piece. The sound outlet 16 shown on the ear-piece provides the acoustical stimuli, generated by the device, to the user. The speaker (or receiver) of the device may be placed in the behind-the-ear part 12 and then connected to the ear-device through a sound tube, or the speaker may be placed in the ear-piece. The sound-outlet 16 may also provide an acoustical feed-through (vent) in order not to occlude the ear. The wire/sound-tube is a sound-guide in the case where the speaker is placed in the behind-the-ear device. If the speaker is placed in the ear-piece the wire/sound-tube is an electrical wire. The signal acquisition, i.e. pre-amplifier and analogue to digital converters (ADC's), may be placed in the ear-piece 15 or in the behind the ear part 12. The behind the ear part 12 may comprise a microphone for the purpose of measuring the sound pressure level of the user's environment. In this way the sound level from the device can be adapted to the sound pressure level of the user's environment. This may be advantageous both with respect to the audio stimuli for the electrode test, and for audio messages from the device to the user.

Figure 4 shows a further embodiment of an EEG monitor device 1. The device has electrodes 3 on the ear-piece 15 as the embodiment of figure 3, but is also provided with a pad electrode 20 connected to the behind the ear part 12 through a wire 21. Such a pad electrode can be arranged on the skin surface of the head in a point outside the ear canal. This can be relevant for surveillance of conditions where the EEG signal from a given region of the brain is relevant, and the signal obtainable from the ear canal is not sufficient.

In the practical implementation of the invention the electrodes may also be placed at e.g. the surface of a housing for the electronics, e.g. a behind the ear part 12.

Figure 5 shows a completely in-the-ear embodiment of an EEG monitor device in a cross sectional view. The device is housed in a custom made ear piece 25 as known from in-the-ear hearing aids. The contours of the outer surface 26 of the ear piece are manufactured to follow the contours of at least part of the ear canal and the concha of the user. The electrodes 3 are embedded in the part of the ear piece 25 outer surface 26

that is matched to follow the ear of the user. The device also comprises an electronic module 27 e.g. comprising different blocks of figure 1 or 2, a microphone 8 and a speaker or receiver 2. The sketch shows electrical wires connecting the electrodes 3, the microphone 8 and the speaker 2 with the electronic module 27. The electronic module
5 comprises means for data acquisition, signal analysis and electrode validation. The ear piece has a ventilation channel 24 for the purpose of avoiding acoustical occlusion of the user's ear-canal i.e. blocking of the ear canal. Further the ear piece has an opening 13 for the microphone 8 and an opening 16 for the receiver 2.

10 Figure 6 shows a layout for the alpha-band detection scheme. This could be applied when the electrode validation is based on an open/closed eye scheme. Instructions are given to the person through the speaker (receiver) 2. The instructions may be that the eyes should be closed, and after a given period the instruction could be that the eyes should be open. This could be repeated for a number of cycles. For each cycle the
15 frequency analysis of the EEG signal is performed separately.

Alpha waves in EEG predominantly originate from the brain during wakeful relaxation with closed eyes. By instructing the user to "open" or "close" the eyes a simple induced by instruction paradigm is established. Thus by comparing the frequency distribution
20 between open eyes epochs and closed eyes epochs it is possible to make a reliable and robust electrode test.

Figure 7 shows three examples of block diagrams for the frequency analysis blocks in figure 6. The alpha-band bandpass filter in figure 7.a has a pass band in the 8 – 12 Hz
25 frequency range. The second block in figure 7.a is a first norm or the absolute value of the signal. The lowpass filter in figure 7.a is averaging the signal. This lowpass filter could be a first or second order recursive filter.

In figure 7.b there is two branches where the top branch finds the energy in the alpha
30 band and the branch below finds the energy outside the alpha band. The first block in the top branch is a bandpass filter allowing frequencies in the alpha band to pass. The first block in the branch below is a bandstop filter blocking frequencies in the alpha

band but allowing other frequencies to pass. The second block in both branches in figure 7.b calculates the Root Mean Square of the signal.

Figure 7.c shows an embodiment of a Short Time Fourier Analysis. The first block, Warped Delay Line, is a known method for changing the frequency scale in order to obtain a better resolution at low frequencies.

Figure 8 shows Power Spectrums from an in-the-ear type Ag-electrode. The signal is sampled at 512 Hz. In the first 30 seconds the person has the eyes closed and in the next 30 seconds the person has the eyes open. The two curves show the Power Spectrum for the first and the second 30 seconds time windows. The Power Spectrum is computed using the Welch method with window length 512 samples, Hamming-window, and 50% overlap between windows. There is a clear difference between the "open eyes" and "closed eyes" power spectrum in the alpha band (frequency range of 8 - 12 Hz).

Figure 9 shows the time frequency plot for the same signal as in figure 8 but re-sampled to 64 Hz sample rate. The spectrogram is computed using the Short Time Fourier Transform (STFT), 512 samples in each window, and 64 new samples in each STFT. There is a clear increase of signal level in the alpha band for the open eye sequence compared to the closed eye sequence.

Figure 10 shows the same signal as in figure 8 and 9. The curve shows the power of the alpha band (8 - 12 Hz) computed from the corresponding taps of the STFT from the spectrogram shown in figure 9. The curve shows a significant drop in alpha band power at 30 seconds, where the eyes are opened.

Figure 11 shows a simple one dimensional binary classifier for the alpha band detection scheme. The grey bars represent the histogram for the power in the alpha -band for the "Open eye" data and the black bars represents the histogram for the "Closed eye" data. The dashed line shown is the discrimination level which results in the classification performance printed in the small table in the left part of figure 11. It is seen from this

table that the specification and the accuracy are relatively good, implying that two measurements usually will be sufficient.

Figure 12 shows depiction of a two dimensional binary classifier for the alpha band
5 detection scheme. The plot is a scatter plot where the dots represents data points in the
feature space (dimension 1 versus dimension 2), and the solid line is the linear
discrimination line. The black and gray dots represent data points from class 1 and 2
respectively. Figure 12 shows a simulation example where the detector has two inputs;
e.g. dimension 1 is the power from the alpha band and dimension 2 is the power from
10 all other frequency bands. This could be obtained by the block diagram in figure 7.b
where the top signal branch in figure 7.b provides dimension 1, and the below signal
branch in figure 7.b provides dimension 2. In this example "Class 2" would be the
"Closed eye" data and "Class 1" would be the "Open eye" data. This can be further
generalized to non-linear classifiers, and to higher order linear or nonlinear classifiers.

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The electrode validation may also be performed by a combination of different methods.
E.g. the method based on generated audio-stimuli and the method based on ambient
sounds may be combined. One example of such a combined system could be that the
electrode test based on generated audio signals is performed when the device is
20 switched on or whenever the user requests an electrode test. The electrode test based on
the ambient sound environment will run continuously whenever the device is in use.
The methods based on induced responses may also be combined with electrical
impedance measurements. The advantage of combining different measurement methods
is that this may improve the electrode validation in terms of reliability, robustness, the
25 ability to distinguish between different fault causes etc.

Electrode validation based on electrical impedance measurements can also be
implemented to be active continuously and at the same time as when measuring EEG
signals. This is possible if the electrical signal applied to the electrode for measuring
30 the impedance is in a frequency range outside the frequency range where the EEG
signal is of interest. Typically the electrical signal can have a higher frequency, such as
500 Hz or more, than the frequency range where the EEG signal is of interest.

Alternatively to selecting a different frequency for the impedance measurement, the EEG monitoring could be interrupted for a short period while the impedance measurement is performed. In that case the frequency of the impedance measurement could typically be in the range 10 – 30 Hz.

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In the event that the electrode validation system cannot establish that the electrodes receive an EEG signal a notification could be given to the person wearing the EEG monitor. This will enable the person to adjust the position of the EEG electrodes in order to make sure that there is a good electrical connection between the electrodes and the skin. The notification could be in the form of a sound message, e.g. a voice message
10 informing the person what to do.

Claims

1. A personal wearable EEG monitor adapted to be carried at the head of a person, said EEG monitor comprising
 - EEG sensor part having skin surface electrodes for measuring one or
 5 more EEG signals from said person, wherein at least one electrode is adapted to be arranged in an ear canal of said person;
 - EEG signal analyzer adapted for having an EEG signal transferred from said EEG sensor part, and adapted for monitoring the EEG signal from said person,
 - 10 – EEG stimuli controlling means adapted for performing at least one of the following:
 - providing an auditory stimulus to said person from an auditory stimulus means in the ear canal of said person,
 - requesting said person to perform a stimulus-creating act,
 - 15 - identifying a potentially stimulus-creating ambient sound,
 - EEG response detection means for identifying an induced response from the EEG signal caused by said stimulus, and
 - a classifier for deciding based on said at least one induced response if said skin surface electrodes receive EEG signals of said person.
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2. An EEG monitor according to claim 1, wherein the electrodes are dry electrodes.
3. An EEG monitor according to any one of the previous claims, wherein said
 25 EEG stimuli controlling means is adapted for identifying sounds from the surroundings capable of causing an induced response.

4. An EEG monitor according to any one of the previous claims, wherein said EEG stimuli controlling means is adapted for requesting said person to open and close the eyes.
- 5 5. An EEG monitor according to any one of the previous claims, wherein said stimulus is repeated at least two times.
6. An EEG monitor according to any one of the previous claims, wherein said at least one electrode adapted to be arranged in the ear canal is arranged on an ear-
10 piece, said ear-piece being provided with a permanent shape fitting the ear canal of said person.
7. An EEG monitor according to any one of the previous claims, further comprising a pad electrode external to the EEG sensor part, said pad electrode
15 adapted to be arranged on the head of the person to be monitored.
8. An EEG monitor according to any one of the previous claims, adapted for testing the validity of at least three electrodes simultaneously, by identifying induced response.
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9. An EEG monitor according to any one of the previous claims, wherein validation of electrodes by identifying induced response is combined with measuring the electrical impedance between electrodes placed on the skin surface.
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10. An EEG monitor according to any one of the previous claims, comprising notification means for notifying said person if the EEG signal is not received.
11. An EEG monitor according to any one of the previous claims, comprising
30 means for identifying electrodes receiving an EEG signal and selecting these electrodes for monitoring the EEG signal from said person.

12. An EEG monitor according to any one of the previous claims, comprising means for transmitting a wireless notification to an external unit in the event that the EEG signal is not received by the electrodes.
- 5 13. A method for continuously monitoring EEG signals of a person by an EEG monitor carried at the head of said person, said method comprising the steps of
- measuring one or more EEG signals from said person by an EEG sensor part having skin surface electrodes, wherein at least one electrode is adapted to be arranged in an ear canal of said person,
 - 10 – transferring an EEG signal from said EEG sensor part to a processing unit having EEG signal processing means,
 - monitoring the EEG signal from said person in said processing unit,
 - causing an induced response in the EEG signal by performing at least one of the following:
 - 15 - providing an auditory stimulus to said person from an auditory stimulus means in the ear canal of said person,
 - request said person to perform a stimulus creating act,
 - identifying a stimulus creating ambient sound,
 - identifying an induced response from the EEG signal caused by said
 - 20 stimuli, and
 - deciding based on said induced response if said skin surface electrodes receive EEG signals of said person.
14. A method according to claim 13, comprising notifying said person if the EEG
- 25 signal is not received by said electrodes.
15. A method according to claim 13 or 14, comprising identifying the specific electrodes receiving an EEG signal.

16. A method according to any one of claims 13 to 15, comprising reconfiguring the EEG monitor to measure the EEG signal by selecting electrodes receiving an EEG signal.
- 5 17. A method according to any one of the claims 13 to 16, comprising repeating the steps of causing an induced response in the EEG signal and identifying an induced response from the EEG signal at time intervals either preselected or adjusted according to previous decisions if said electrodes receive EEG signal.