Portable Electroencephalogram Biofeedback Device

Final Report

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BME 200

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§1. Abstract

Biofeedback is a therapy currently being researched to treat many psychological and physiological disorders. It is not known how attempting to control autonomic functions of the brain may help resolve abnormalities, but results overwhelmingly point towards biofeedback's legitimacy. EEG biofeedback involves the monitoring and altering of brain activity and has been shown to effectively treat such problems as epilepsy, mood disorders, addictions, and attention-deficit/hyperactivity disorder. The majority of EEG biofeedback devices are designed for use in clinical situations by experience personnel. To apply this technology to a personal setting, an inexpensive and user-friendly device is required that can process brain signals and provide logical interpretations of the recorded activity. Several electrode types and feedback mechanisms, as well as a design for high-gain amplifiers, have been researched and analyzed. The current early prototype design and anticipated future work are also discussed.

§2. Problem Statement

The goal of our project is to design and build an inexpensive, portable electroencephalogram (EEG - brain wave monitor) that teaches meditation practitioners to achieve optimal meditation by the recognition and promotion of EEG alpha and theta waves.

§3. Introduction

Pharmacological therapies have been the standard way of treating most types of disorders and syndromes. However, alternative therapies are currently being prescribed by physicians as a new approach to healing and include such treatments as acupuncture, chiropractics, and biofeedback. These treatments' mechanisms are not very well understood, but results demonstrate promising progress in patient rehabilitation.

One of the most promising of these newly developed alternatives, biofeedback allows the user to view their own autonomic physiological changes. Physiological variation like pulse, blood pressure, respiratory rate, and brain activity can be monitored and eventually controlled through conscious practice of recognition and propagation of healthy ranges of such bodily functions.

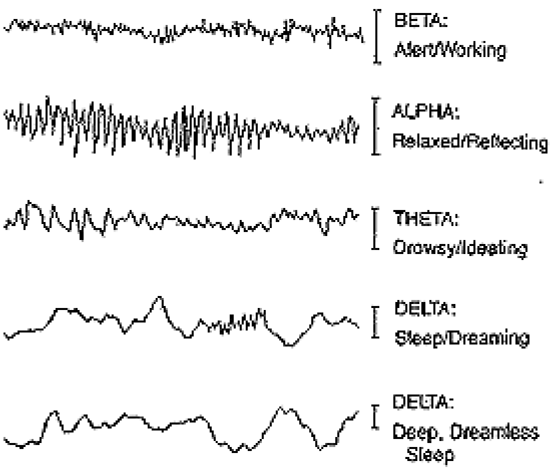


Figure 1. Raw EEG Data

Our client, Dan Muller, M.D., Ph. D., frequently prescribes meditation as a means of mental health management. In order for inexperienced patients to learn how to meditate, a device is needed to tell the user exactly what type of activity their brain is currently undergoing.

When meditation occurs, a specific frequency of waves is observed in the brain. Typical active brain waves are called beta waves and vary between 15-40 Hz. Relaxation and drowsiness are noted as alpha waves in the 8-15 Hz range. Meditation occurs in the theta waveform at 4-7 Hz.

In order to monitor neuro-biofeedback, electroencephalographs (EEGs) are used to measure surface voltages on the scalp caused by neuron action potentials in the brain. These cellular action potentials directly relate to the qualitative and quantitative aspects of brain activity, reflecting the mental state within discrete frequency ranges.

When the user can quantitatively observe the state that their brain is in, they can begin to coach themselves into lower frequencies of brain activity without the aid of a biofeedback device. This allows the user to achieve a theta waveform/meditation much faster and with greater ease in the future. With frequent use, EEG biofeedback has been shown to improve a variety of ailments such as addictions, mood disorders, epilepsy, and attention-deficit/hyperactive disorder (Raymond, 2005).

§4. Literature Search

A patent search revealed several methods (6,855,112; 5,450,855; 5,280,793) for regulating neural responses via monitoring them on a display for the purposes of biofeedback.

Commercially available products are very expensive and are not typically EEG specific. For instance, the Stens NeXus-10 serves as an electroencephalogram (EEG), electrocardiogram (ECG), electromyogram (EMG), and slow cortical potentials (SCP). This device, while providing professional grade quality, will also run the buyer $4395. C2 and ProComp also manufacture high quality EEG biofeedback devices starting at about $2000.

§5. Design Constraints

The portable EEG (brain wave monitor) will take an incoming signal from a series of electrodes, amplify the signal to measurable and interpretable levels, filter out specific frequencies and present the occurrence of those distinctive brain waves in a manner applicable for biofeedback.

The device should also be small and portable, have the ability to be used daily, have a relatively simple interface, and be comfortable, as it will be used while meditating. In order to conserve costs, internal and external parts need to be as simple and minimal as allowed.

All aspects of the device need to be in compliance with AAMI and FDA standards and regulations for related devices.

§6. Proposed Designs

The EEG biofeedback device is actually an accumulation of three different areas of designs; electrodes for signal acquisition, an amplifier to create signal amplification and processing, and a biofeedback method for signal feedback. Described here are the individual designs for each.

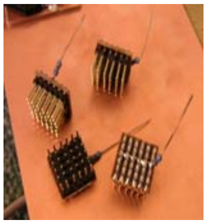
§6.1 Electrodes

The previous years’ electrode design consisted of an elastic headband with two electrodes made of coiled wire folded over a felt surface and covered by another layer of felt. Another option that they mentioned was the use of an array of conducting probes which protrude through the hair to make direct contact with the scalp. As per their report, they could not get a good signal from these electrodes. Hence, in fall of 2005, we decided to develop a new design for the electrodes. The electrodes should be highly conductive, easy to use and inexpensive at the same time.

In the process of brain-storming, developed three main electrode styles, including plate/disc electrodes, pin electrodes and sponge/coaxial electrodes. The plate electrode consisted of a flat disc/plate generally around 6-10 mm in diameter and made of either gold or silver to serve as an excellent conducting material. The electrode had a hole at the top for

(http://www.electrodestore.com)

electrolyte injection which provided better conductivity and signal quality. The electrode required electrolytic gel for conductivity and adhesive properties. This design was not used for practical reasons, as the electrodes are difficult to attach to the scalp and the gel leaves the hair oily and sticky.


(http://openeeg.sourceforge.net)

The next design we came up with was the pin electrode. This design consisted of a basic array of metal conducting pins fixed to a square electrode baseboard. One hole was drilled in the electrode baseboard, a square piece of circuit board, for each of the 16 to 32 pins in the electrode. Two of these electrodes were mounted on a headband and held firmly against the scalp. The electrical signal from the brain was then measured by the electrode and transmitted to the amplifier. The main advantage to this design was that it did not require electrolyte gel for conductivity.


(http://openeeg.sourceforge.net)

The third design consisted of a series of four to six homemade passive electrodes contained by a plastic headband. Coaxial cable was stripped down to leave a stem of wire exposed, which was covered by foam rubber ear plugs (or other suitable porous and soft material) to ensure comfort and improved contact. To sufficiently measure small voltage differences in pertinent areas of the brain, the array of electrode "plugs" are arranged in an arch over the upper frontal portion of the head, representing only a portion of the typical layout of electrodes used in clinical applications. The signal would be carried directly through copper wire to the device housing the amplifier, therefore reducing disturbances or noise a built-in amplifier or other source of interference would create.

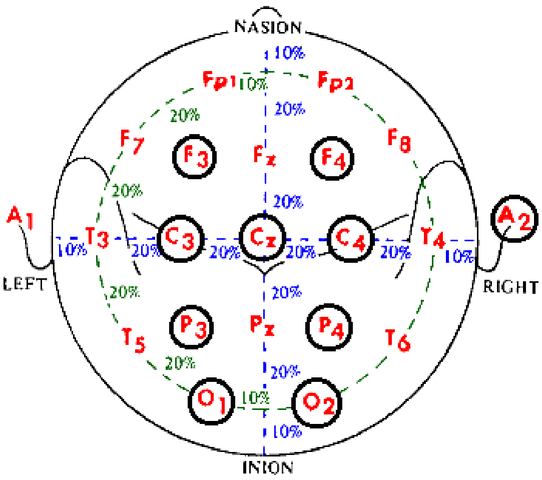
Design Matrix

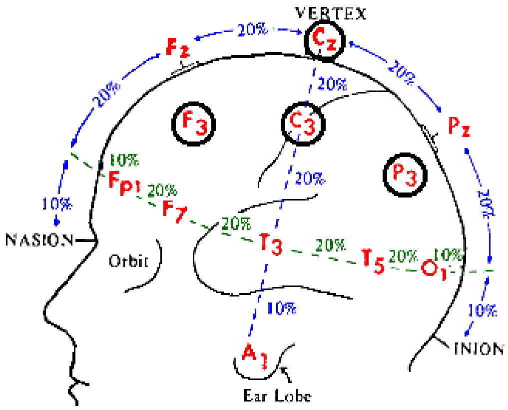
	Ease of manufacture	**Comfort**	**Preparation simplicity**	**Cost**	**Aesthetics**	**Durability (reusability)**	Overall
Coaxial cable headband	8	6	8	9	7	8	7.6
Pin electrodes	2	4	10	4	7	10	6.2
Plate electrodes	10	4	2	1	3	6	4.3

We tested each electrode and gave points for each category from 1-10 where 10 represented the most optimal value. Both the coaxial cable and pin electrodes reasonably matched our project design goals, but we decided to develop the coaxial cable design because the pin setup involved active electrodes that require mastery of complex circuitry and would have been difficult to use with our design.

Modified Final Design

Our final design was quite similar to the third proposed design shown; instead of five electrodes, only three are used. Silver wire comes out of the hole created by coaxial guides and is responsible for conductivity. The signal is propagated through a simple salt solution on the surface of commonly available foam ear plugs attached to the end of each silver lead wire. The ear plugs are fully detachable where a small hole is established through each to aid in sliding it over the silver wire without making the setup permanent; the ear plugs therefore can be easily cleaned or replaced as the situation demands. Copper wires are sautered to the short silver sections and connect directly to the amplifier. The position of the three electrodes follows by the international 10-20 system for the placement of electrodes in EEG recordings. Placed on the upper frontal part of the head approximately 20º from vertical, the electrodes are represented by C_3, C_Z and C_4 in the figure below, with C_Z serving as the midline electrode.





Electrolyte Solution and Conductivity

In order to cut down the cost of the design, we were required to use an electrolyte which can be easily available and does not require any chemicals. Therefore, we decided to use salt water solution for the electrolyte as it is a good conductor. In our experiments, a 2% salt solution in distilled water was used for soaking the ear plugs. Surprisingly, the plugs had a tremendous capacity for retaining water, holding the solution for more than 1 hour even when left out in the open.

§6.2 Amplifier

Due to the minute scale of the potentials to be measured on the scalp, the electrode signal must be amplified before it can be analyzed or processed. Using an amplifier is one way to enhance the signal provided by the electrodes through a voltage increase, making the output much more practical for analysis.

Several amplifiers were researched including the basic instrumentation amplifier as well as a “minimal parts” amplifier proposed by VanRijn. Our design utilizes a combination of both approaches.

This amplifier is to be used in a personal device designed for qualitative analysis. With this in mind, it is in our best interest to keep the design simple, sacrificing accuracy for lower cost. This is especially important to consider since the device is intended for recreational, non-clinical use. While considering the previous groups’ designs, it was decided to move back to the most basic design and proceed from there.

While the amplifiers discussed above have produced results, there are several things that need to be carefully looked at. Amplifier saturation is a large problem especially when considering an EEG signal needs to be amplified 10,000-100,000 times. Simple muscle contractions can produce potential differences on the order of 1-100 mV and can easily cover the microvolt signals we will be monitoring.

Our design is an amplifier in two stages. The first stage is a differential amplifier with modest (50x) gain, and the second stage is a simple non-inverting amplifier that will produce the remaining gain required (2000x). The differential amplifier analyzes the potential difference between each of two electrodes and compares them to a common third electrode which serves as a ground. The frequency bandwidth is shaped by first a high-pass filter followed by a low-pass filter integrated with the design. This type of amplifier is commonly referred to as a band-pass amplifier because only certain frequencies are amplified, while the rest are attenuated.

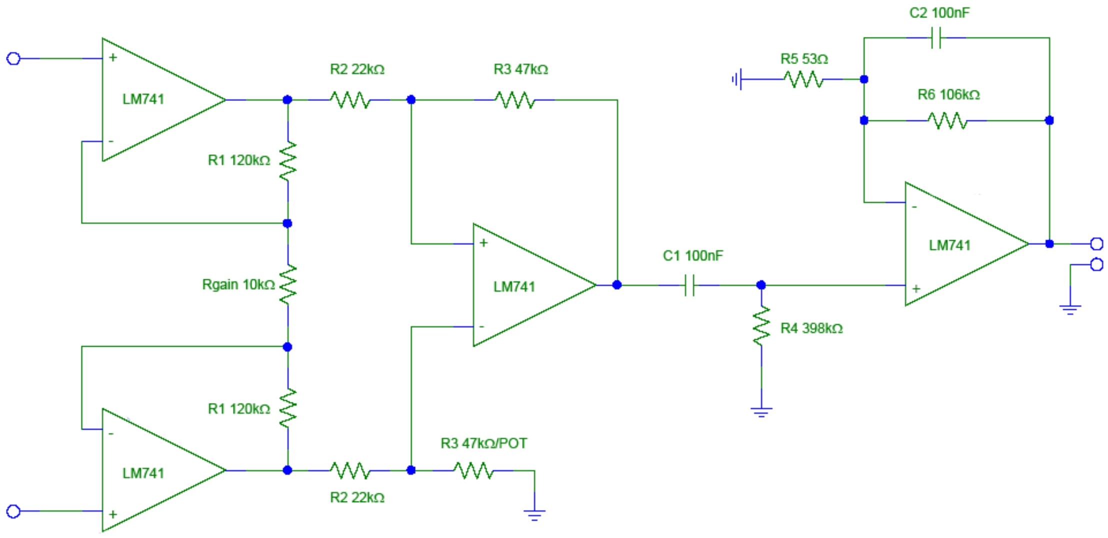


Figure 2. A diagram of our proposed circuit, based off a common instrumentation amplifier.

Basic circuit analysis provides us with several equations for the properties of this amplifier.

$$Gain = \left[\left(1 + \frac{2R_1}{R_{Gain}} \right) \frac{R_3}{R_2} \right] \frac{R_6}{R_5} \qquad f_{low} = \frac{1}{R_4 C_1 2\pi} \qquad f_{high} = \frac{1}{R_5 C_2 2\pi}$$

Currently the amplifier is designed to pass only the relevant frequencies, in this case the frequencies of theta (4-7 Hz) and alpha (8-15 Hz) waves. The equations above were solved for an f_{low} of 4 Hz and an f_{high} of 15 Hz. Adequate gain will amplify µV signals from the electrodes to 0.1-1 V signals for analysis. Using the values shown in Figure 6, our gain is on the order of 10^5. The CMRR should be kept as high as possible for more accurate readings.

Component matching problems can also be addressed by using potentiometers in place of certain resistors, and “tuning” the circuit for best results. For this reason, the R_3 connected to ground was replaced with a potentiometer that is used to zero out any error introduced by the 5% tolerance found in the resistors used. If the circuit were to be rebuilt and tested, a potentiometer might have also been used for R_{gain}. This would allow the final gain to be adjustable, which would have been very helpful during the testing. The fixed gain in the design currently meant that 100:1 or 1000:1 attenuators needed to be used since the testing input waves’ quality was compromised at low voltages.

§6.3 Feedback Method

Feedback was previously approached by past groups through the use of LED glasses in which the intensity of the light represented the frequency of the brain waves. We decided to stray from this design due to the necessity of keeping one's eyes open to accurately distinguish the changes in intensity of the LEDs during use.

The proposed design for the biofeedback device is made simpler by using an audio signal. The audio signals pitch will aid the user in gauging how relaxed they are while eliminating the distraction caused by visual input. As the user becomes more relaxed and their brain waves decrease in frequency, the pitch will become lower.

This effect should be achieved using frequency multipliers which translate the relatively slow brain waves (4-15 Hz) into audible tones (>~30 Hz). The circuitry of the biofeedback method as well as the tone quality of the raw EEG data have yet to be developed or further researched in this semester's work.

§ 6.4 Current Prototype

Figure 3. Integrated protoype with electrodes, amplifier, and battery power source.

§7. Testing

Testing of the electrodes and amplifiers took place in several different steps. The first tests conducted involved using a pre-made ECG amplifier and adhesive Ag/AgCl ECG electrodes. The amplifier was connected to a 12 V power supply, an oscilloscope, and three electrodes, one of which was used as a common mode. The electrodes were placed on the forehead of a human subject, and readings were taken. Measurements from the oscilloscope were inconclusive, showing exclusively 60 Hz interference and noise.

The next series of tests involved using our final design for the electrodes and the same ECG amplifier used earlier. The same setup as the previous testing session was used, except that the electrodes were placed on the top of the head as opposed to the forehead. The test results achieved during this session were more conclusive. A strong signal was outputted to the oscilloscope, and although it was still masked by noise, a partially discernible bioelectric signal could be seen. This is strong evidence that our electrode design works. However, because the ECG amplifier was designed only to amplify a signal, and not to filter out any frequencies, the noise was too great to reach any definitive conclusions.

The final series of tests were conducted with our completed final design. The amplifier was connected to a 10 V power supply, an oscilloscope, and the three electrodes attached to the headphones. The signals from the left and right electrodes were measured against the central electrode, which acted as a ground. These tests were not as conclusive as the previous round of testing. The results shown on the oscilloscope mirrored the first series of tests, in that they were almost completely overrun with noise. A varying signal could be seen when tapping the electrodes with a finger, but when the electrodes were kept still, no discernible signal could be read. One potential reason for the excess of noise was that the amplifier was directly connected to a power supply and oscilloscope that were powered from wall outlets, introducing unwanted 60 Hz interference. Our final design would eliminate this problem by being completely self-contained and powered by a battery.

In the end, our testing proved mostly inconclusive. The majority of the results were overrun with noise which may have been introduced by the wall outlets. However, a discernible bioelectric signal was seen in one stage of testing, providing evidence for the functionality of the electrode design. Further testing with more sophisticated equipment is necessary to more accurately finish development of the amplifier design.

§8. Future Work

§8.1 Signal Acquisition

Our current electrode setup involving silver wire and foam ear plugs soaked for approximately five minutes in salt water appears to be effective after tests have demonstrated that a signal can successfully be obtained. However, interference occurring at some stage of the testing has been a consistent barrier in our design process. Due to the nature of the instruments we have available to test the electronics, it is difficult to determine the source of the problem. Future goals in this area include finding suitable a waveform generator and oscilloscope setup (preferably battery-run to minimize interference from external power sources) to test our prototype in order to confirm that our current design produces a clear and usable signal.

§8.2 Signal Conversion to Feedback

Once the EEG signals have been amplified, they need to be interpreted in some manner to produce a logical output for the user. The signal from the amplifier can be processed using either digital or analog techniques. Digital signal processing offers more versatility at the cost of more expensive and complicated implementation. Analog processing offers simple and cost effective alternative, but limited and difficult integration with the eventual feedback mechanism.

Digital signal processing first requires an analog to digital conversion. This is a method of turning a continuous analog signal into a series of values encoded as bits. In this conversion, there are several properties to consider. The practical frequency of the digital signal is the analog frequency that can be accurately reproduced by the digital converter, which only records periodic values of the original signal. The signals we are all interested in are all well below 50 Hz, so only a relatively low practical frequency is needed. Practical frequency is determined by several factors including speed, resolution, and step recovery time.

There are several methods for analog to digital conversion, all with different properties. The Flash, or Parallel, analog to digital converter (ADC) is the best solution for our project due to its speed and price. The flash ADC uses a series of comparators which are fed into a priority encoder. The priority encoder can be replaced with a series of Exclusive-OR gates and diodes to reduce costs. The downside to this method is the number of components required (allaboutcircuits.com). Other less suitable implementations include the digital ramp,

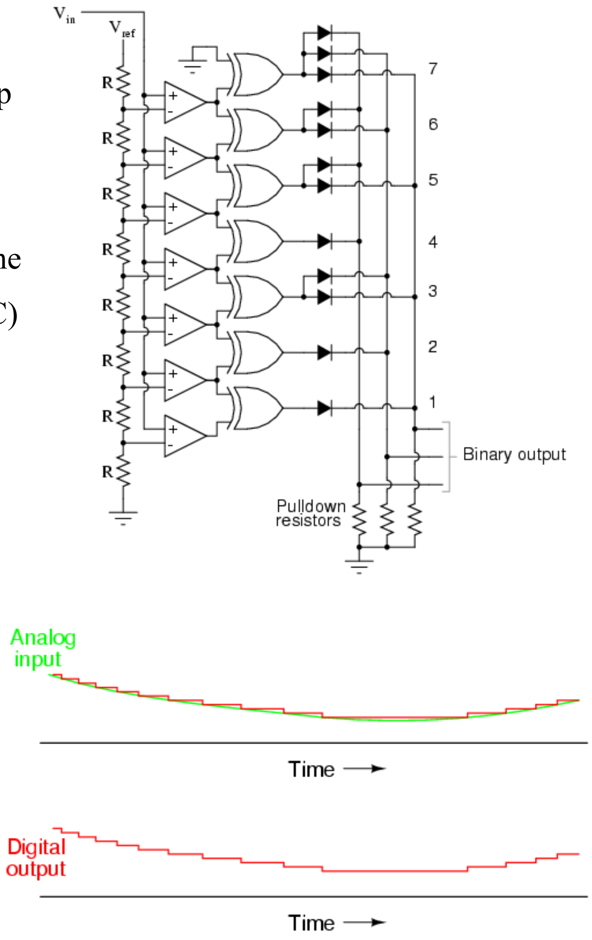


Figure 4 - (top) An example of a Flash ADC implementation using a series of comparators, Exclusive-OR gates and a diode matrix. (bottom) The digital output of a Flash ADC as it corresponds to the analog input.

http://www.allaboutcircuits.com

integrating (slope), tracking, and delta-sigma ADCs.

Once the analog signal has been converted to a digital series, it must be interpreted by a processing algorithm. The signal could initially be input into a computer via a Labjack, and eventually USB for consumer use. A computer application would then use an algorithm, such as a Fourier transform, to interpret the content of the signal. Finally, the computer would output a corresponding signal to the feedback mechanism. This offers incredible versatility for the feedback methods, and even support for modular feedback devices. Eventually, the computer could even be replaced with an embedded system so that our device would remain portable and self-contained.

The second option for signal processing involves analog filters. The amplifier signal would be split, and fed into two filters, each consisting of a high-pass and a low-pass filter. One filter would extract the alpha waves, while the other would extract theta waves, according to their frequency. These signals could then be rectified and processed into a DC current in proportion to the strength of its associated frequency. Voltage to frequency converters would produce a frequency that was dependant on the input DC current. This frequency could then be output directly to the feedback system (headphones), and would lower as the input voltage rose in response to stronger alpha and theta brainwave activity.

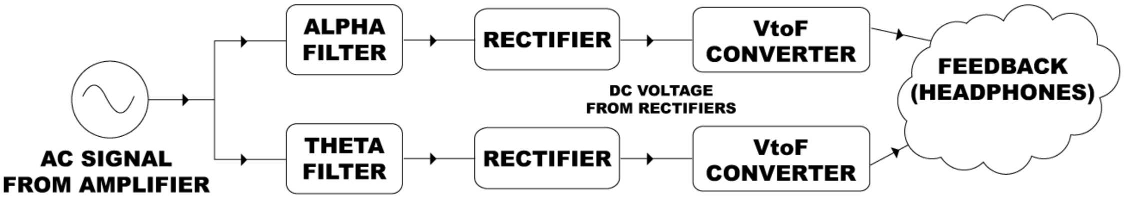


Figure 5 – A block diagram showing the path of the signal through an analog filtering circuit.

Despite the complicated implementation, the versatility of digital signal processing promises a much more desirable product with a minimal price increase. The prospect of modular output is appealing because it would provide each user with multiple options for feedback, and thus a less-invasive, more effective device. Further design of a specific flash ADC implementation needs to be created, and interpretation methods and software needs to be developed.

§8.3 Aesthetics

The prototype constructed for the project this semester is built upon a very small, simple headset, which doesn't properly contain the electronics involved in this device. Our electrodes and amplifier were constructed on a relatively large scale, and further development could lead to a smaller profile for both. In addition, the ideal prototype would be built upon a larger pair of headphones where room within the headband would be used to hide unsightly circuitry. If the device can be self-contained with electrodes, amplifier, power supply, and signal conversion hidden from the viewer, the overall meditation experience may be improved.

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§10. Product Design Specifications

Portable Electroencephalogram Biofeedback Device
PRODUCT DESIGN SPECIFICATION

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Last update: 09/30/2005

Function: The portable EEG (brain wave monitor) will take an incoming signal from a series of electrodes, amplify the signal to measurable and interpretable levels, filter out specific frequencies and present the occurrence of those distinctive brain waves in a manner applicable for biofeedback.

Client Requirements:

- A device that minimizes complicated user input (simplistic like an iPod)
- Final cost of $100-200
- A type of biofeedback output that is not distracting to the user during meditation

Design Requirements:

Physical and Operational Characteristics

- Performance: Device should be able to be used for a minimum of two hours on a single battery charge, with the possibility of daily use.
- Aesthetics, Appearance, and Finish: Device should be minimally complicated visually, with an interface similar to that of portable music players (such as an iPod). The shape should be rectangular, and colors should be pleasing to the eye without being distracting.
- Safety: Device should be free from danger of shock, and be appropriately labeled to warn of this danger as well as damaging interaction with electrical components.
- Size & Weight: Device should be portable and easy to transport.
- Accuracy and Reliability: Device should produce feedback accurate enough for qualitative analysis, not necessarily clinical applications.
- Operating Environment: Device should be able to be operated by one person, in reasonable indoor/outdoor conditions (not extremes such as in rain/bathtub), and be able to withstand the typical wear associated with accidents and everyday use.
- Materials: Should incorporate a maximum number of reusable parts.
- Life in Service: Device should last a minimum of 5 years.

Production Characteristics

- Quantity: The portable EEG will be relatively mass-produced for consumer delivery.
- Target Product Cost: $100 - 200, compared to commercial versions ranging from $1,000 – 5,000

Other Characteristics

- Standards and Specifications: Meets national standards for electronic devices, as well as FDA requirements (Level 1 or 2?).

- Customer: Device should be conducive to a meditative environment (comfortable, a user-friendly, simple interface)
- Patient-related concerns: Preparation of the electrodes may be extensive, requiring daily cleaning, and eventual replacement.
- Competition: Should be able to produce comparable signal quality and feedback for a lower price, smaller packaging, and no necessary training.
  N.B. A patent search found a similar device using rapid LEDs as the feedback mechanism.