RECENT ADVANCES IN EEG MONITORING FOR GENERAL ANAESTHESIA, ALTERED STATES OF CONSCIOUSNESS AND SPORTS PERFORMANCE SCIENCE

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ABOUT ALPHA-ACTIVE LTD

Alpha-Active Ltd is a company dedicated to the design and provision of brainwave monitoring and training products in sports and therapeutic applications.

Who can benefit:

Potentially the main field of application of Alpha-Active is in helping individuals to achieve their personal best consistently in challenging situations. These include sporting events, appearing in front of the public (e.g. performing arts, speeches, business meetings, etc.), and in any stressful situation where clear focus and composure are required. In the sports field, this is often known as being 'in the zone'.

Alpha-Active technology may also be potentially beneficial as an aid to users for:

- home use (e.g. relaxation, meditation, etc.,)
- assisting practitioners to judge mental receptiveness in a range of neurofeedback therapies (e.g. pain relief, treatment of anxieties, phobias, cessation therapy, hypnotherapy, counselling, cognitive behavioural therapy, etc.,)
- clinical fields (e.g. psychology, determining states of consciousness, detection of drugs use, etc.).

How it works:

An EEG (electroencephalogram) monitors the electrical activity of the brain. Brainwaves may be a measure of a person's concentration or 'focus' and are optimised routinely by sports men and women to improve performance. Alpha-Active's products can be used to monitor changes in brainwaves simultaneous with the carrying out of actions by atheletes etc.

Most EEGs are large, expensive, complicated-to-use, mains-powered devices. Whereas Alpha-Active's range of products builds on patented and proprietary technology and techniques to provide a pocket-sized, robust, cost-effective, simple-to-use, laptop-powered product which can work in the sports field even when athletes are moving about because the software is more robust to the movement of the user. Sophisticated user-friendly software allows sports coaches, practitioners, therapists, etc., and their clients, to relate peaks of performance to EEG recorded at the time - hence providing a 'neurobiofeedback' mechanism to help reproduce the appropriate brainwave activity at key pressure moments - thereby providing the competitive edge.

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Abstract

A novel approach for electroencephalogram (EEG) processing is presented. Along with the theoretical development of stochastic signal processing techniques, three application areas are suggested: general anaesthesia monitoring, altered states of consciousness e.g. hypnosis/sedation and sports performance medicine e.g. training to be in “the zone”. A number of methods already exist to analyze EEG signals. However, they are generally considered to be difficult to interpret and suffer from lack of noise immunity. Spectral analysis certainly aids interpretation but most methods employing the Fast Fourier Transform (FFT) suffer from some well known drawbacks, such as spectral leakage and cross modulation. The method developed here is a modified form of the auto-correlation Yule-Walker algorithm we have named the Bristol Process. It has been found to be stable and able to recover rapidly from even large scale electromagnetic interference (such as surgical diathermy) and from electrical artefacts induced by eye-blinks and body movement. This novel approach permits stable calculation of power relative to total power (an index) at any chosen frequency or frequency band and makes interpretation of EEG easier. Continuous recording of an index (trend) for immediate or post-event review improves interpretation and may be used in association with video recording of sports performance. Future developments are planned with a commercial organisation.

Introduction

Consciousness arises in the brain. The EEG signal is the summation of brain cell synaptic firing originating from the cerebral cortex. General anaesthesia (GA), sedation and hypnosis can be considered to be different states on the same continuum, ranging from death, coma, to full cognitive awareness and beyond to hyper-arousal. There is, however, no readily recognisable component of the raw EEG signal that delineates states along this continuum, but spectral analysis has shown that synchronised firing of neurones can develop into brain rhythms associated with different mental states. An introduction to the EEG is provided by [3].

The major brain rhythm examples, Figures 1, 2, and 3 below, are:

Delta 0.5 Hz to 4 Hz: sleep, general anaesthesia
Theta 4 Hz to 8 Hz: deep hypnosis, dreaming
Alpha 8 Hz to 12 Hz: sedation, hypnosis and relaxed but focused sports activities.
Beta 12 Hz to 22 Hz: high state of arousal and some drug effects.
Gamma 22 Hz to >30 Hz: attention or sensory stimulation.

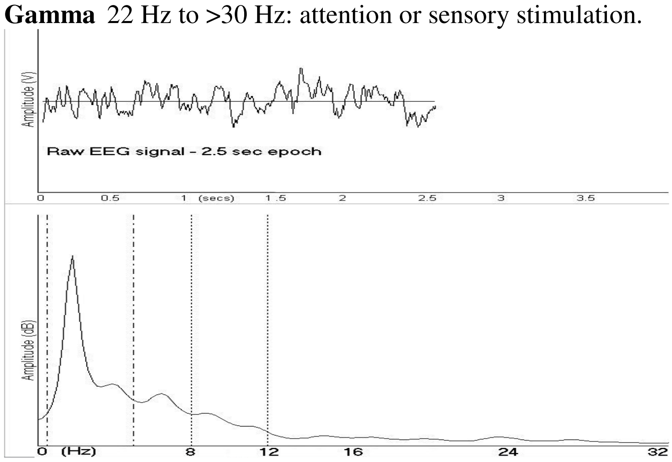

Figure 1: Example of a delta rhythm in a patient under GA. The upper trace is a 2.5 s epoch of the raw EEG signal and is relatively low amplitude. The lower trace is the spectral analysis using the Bristol Process.

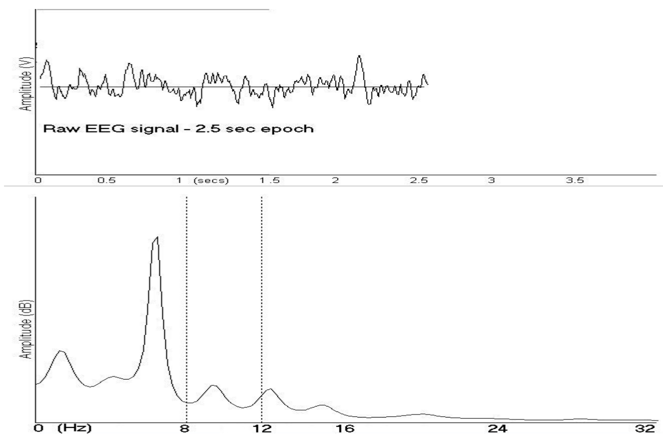

Figure 2: Example of a theta rhythm centred around 6Hz

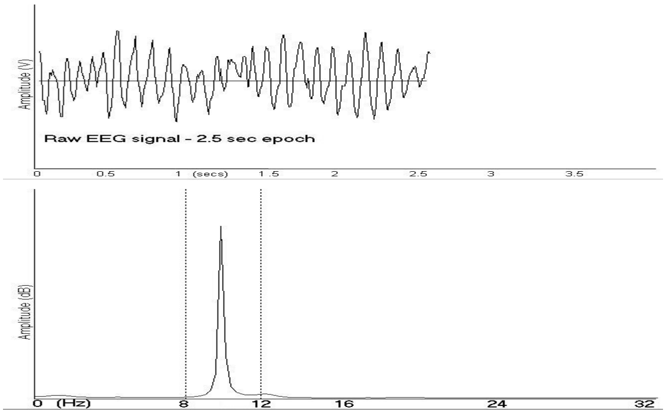

Figure 3: Example of an alpha rhythm. Note the relatively large amplitude and how it varies regularly (so-called "spindling")

The alpha band is of great interest in both medicine and sports science together with the delta band in GA. The conventional way to display an EEG spectrum is using the FFT but this has several problems - spectral leakage, poor performance under conditions of low signal levels (10's of µV) resulting in low signal to noise ratio. Thus stable calculation of power in a rhythm band relative to the total power – an index – is often unreliable using FFT. The shortcomings of the FFT have largely been overcome, for this application, by the Bristol Process, the main subject of this paper, which has high immunity to the major EEG interferences. These are external electromagnetic e.g. mains wiring, fluorescent lights, and from surgical diathermy, and intrinsic body artefacts caused by cardiac signals (ECG), muscle signals (EMG), eye blinks (EOG) and mechanically induced shifts in potential. An operating theatre is an extremely hostile environment for EEG monitoring.

The need for the standard method of attaching EEG electrodes to abraded skin of the scalp by collodion, in order to achieve low impedance for noise reduction, has been obviated in the current work by improvements in front end amplifier design. Modern integrated circuits have wide dynamic range and high common mode rejection ratio, as well as high input impedance giving improved immunity to electrode contact variations. Digital signal processing design using high-resolution analogue to digital converters allows amplifier gain to be reduced and enables larger artefact-contaminated signals, including surgical diathermy, to be rejected. This permits the use of easy-to-affix paediatric ECG electrodes (self-adhesive, disposable, pre-gelled) to the skin of the frontal region and mastoid processes. We have found that, for sports applications, rapid placement of electrodes under a sweatband or cap without elaborate skin preparation is possible. Satisfactory signals can be obtained through thick hair using conductive gel alone.

Analysis of the EEG

Interpreting EEG is difficult but made easier by spectral analysis. Fast Fourier transforms have until fairly recently been the standard method of analysing raw EEG signals. However, in detecting a weak frequency component, corresponding to the emerging alpha rhythm or low frequency delta rhythm induced by an anaesthetic agent, the use of a fast Fourier transforms is unsuitable. There are two reasons for this. Firstly, noise in the brain wave signal is analyzed by the FFT as corresponding to many weak frequency components. Secondly, unless the frequency component being detected corresponds to one of the sampling frequencies of the FFT, the FFT will tend to split a frequency signal into a range of spurious frequency components ("spectral leakage" see figure 4 below).

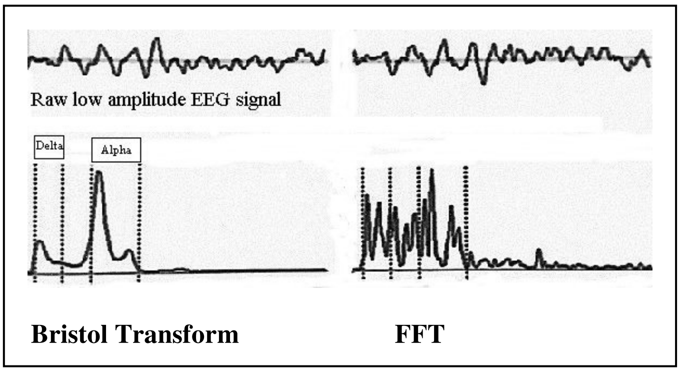

Figure 4: Simultaneous EEG spectral display (on the same screen) of the Bristol Transform and FFT which has multiple spurious peaks. The vertical dotted lines are placed at 0.5, 4, 8 and 12 Hz to delineate the delta and alpha bands. The left raw EEG signal was recorded from the left cerebral hemisphere and the right signal from the right using two channels. Since there was very little difference between the EEG activity in each hemisphere, it was considered to be a valid comparison of the transforms.

The Bristol Process

There is a wide range of algorithms used in digital signal processing to transform time domain signals into the frequency domain. The most common is the Fourier transform. Put briefly, a time series of N samples is assumed to be, whether true or not, a single period of a periodic sequence where each sample is used to calculate the amplitude of N harmonically related sinusoids. There are, of course, limitations to this approach. The most problematic exist as a result of viewing the time series data through a "window" of N samples where data outside the window is assumed to be zero. This causes trade-offs of frequency resolution with time resolution, the loss of data through applying the window and, even more troublesome is the likelihood of causing spectral leakage by truncating what may even be a periodic signal into epochs of arbitrary length.

A more accurate and, as it happens, more computationally efficient approach to transforming stochastic signals, is to use the time series epoch to calculate the amplitude of N exponentially damped sinusoids. The spectrum is then generated as spikes varying in width occurring at the appropriate frequencies. The transformation algorithm in this case operates in the z-plane identifying z-plane poles. The position of each pole describes the centre frequency and the time constant of each damped oscillator. One of the key advantages here is that unlike the FFT the centre frequency of each oscillator is not constrained by a harmonic relationship to one another and thus gives the potential for higher spectral resolution.

Applying an autoregressive difference equation model of the system generating the time series data enables recursive coefficients to be estimated and, based on these estimates, the system poles to be calculated. Expanding the model into a Toeplitz autocovariance matrix gives rise to Yule-Walker equations, which can then be solved by Levinson-Durbin recursion for example, to give the signal spectrum.

This style of solution shows instability under certain conditions. When estimation errors cause calculated z-plane poles to no longer satisfy the rules for stability invalid results are propagated. This deterioration in performance can be seen when the autocovariance matrix approaches a singular form i.e. when the time domain signal approaches pure sinusoidal composition as has been shown to occur in low frequency EEG spectra. Under these circumstances the Yule-Walker equations no longer yield single solutions.

The Burg Maximum Entropy Method improves on the above methods by minimising the amount of estimation required. This approach produces the sharpest spectra of the autoregressive techniques discussed. The main disadvantage of the Burg algorithm in EEG is its handling of signals in noisy environments where spectral line-splitting occurs. All autoregressive models rely on the assumption that the signal is a stationary process to operate correctly. This is regularly not the case in the highly demanding EEG applications discussed here where severe artefact distortion will disturb the underlying statistics of the signal.

Focussing on the described methods in an effort to find a "fix" that may be implemented such that it can cope with the anomalies of the application brings about a trade-off decision between the stability and spectral resolution of each. The relatively tiny bandwidth of interest in these EEG applications relaxes the emphasis on precision frequency resolution whilst the regular artefact signal disturbances require stable handling or, at the very least, fast recovery. In this instance the Yule-Walker method proves most appropriate.

The effectiveness of the Yule-Walker modelling technique in identifying trends appearing in stochastic signals allows the condition of the Toeplitz matrix to be manipulated to a degree without causing significant disruption to subsequent frequency analysis. As such, the deterioration in performance of the Yule-Walker method experienced when the time series data approaches pure sinusoidal content, can be prevented by the application of the Bristol method.

Having addressed the stability of the Yule-Walker method with respect to the transform of EEG signals, the demands of the environment can then be analysed. Each non-ideal element of the signal has been analysed and strategies developed to minimise the disruption they cause. The result is a multi-stage signal-processing scheme that provides enhanced performance in recording EEG spectra in a range of applications.

General Anaesthesia

It has been found that when a person is sedated, but not yet anaesthetised, their brain waves contain a frequency component which occurs between 8 Hz and 12 Hz, and is known as the alpha rhythm. As sedation passes to full anaesthesia, the alpha rhythm disappears. On termination of anaesthesia as the person returns to a sedated state, it reappears and then tends to disappear again when the person is fully awake [5].

It has been realised that this effect may be used to detect any undesired transition from anaesthesia to sedation, corresponding to the person beginning to regain consciousness, for example when a surgical operation is taking place. In addition, the occurrence of new frequencies lower than the alpha band such as delta, induced by the anaesthetic agents can be used to detect the undesirable presence of true anaesthesia if the intention is to maintain a state of sedation. The trial of sedation using a volatile anaesthetic, enflurane [5], showed that it was possible to use EEG monitoring for GA to avoid the shocking consequences of awareness during a surgical operation, estimated in the USA to be 26,000 cases annually [11]. Figure 5 below shows a dominant alpha rhythm in the sedation phase of GA. The two traces are the continuous record (trend) of the alpha index (thick line) and the delta index trend (thin line). The time scale is in minutes. The momentary dip in alpha after 2.5 min was the result of disturbance of the subject by sound.

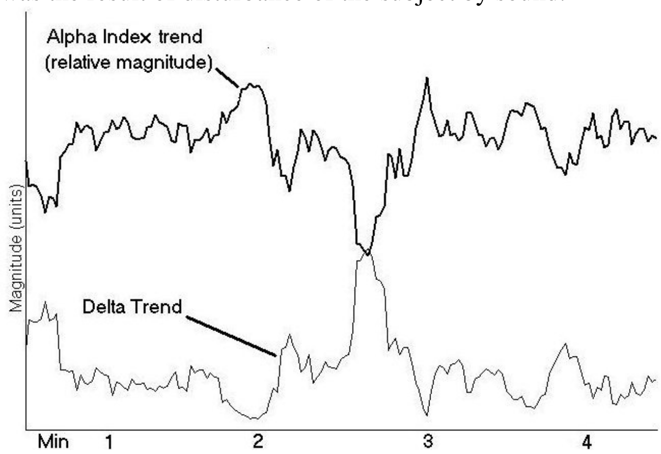

Figure 5: Sedation phase of GA. See text for explanation.

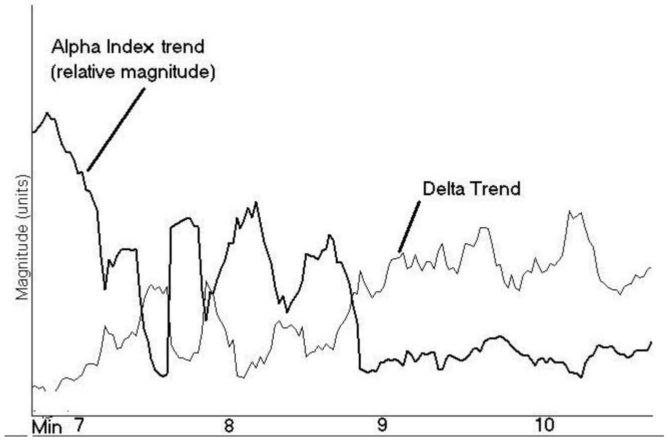

Figure 6: Sedation passing into anaesthesia.

As the anaesthetic agent took effect, the alpha rhythm was suppressed, the amplitude of the EEG reduced and a new rhythm appeared in the delta band. The alpha and delta index trends were reversed in amplitude. Recovery was a reversal of this process, the subject passing through a sedation/alpha state into full consciousness.

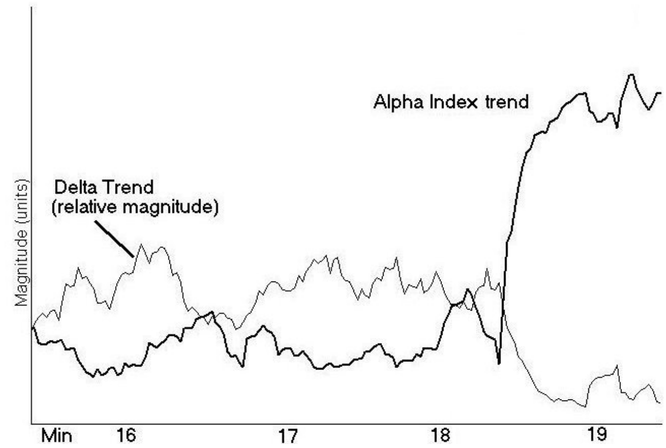

Figure 7: Recovery from GA passing into a state of sedation before full consciousness.

Propofol, an intravenous anaesthetic agent, seems to induce a strong delta response which would enhance the contrast between sedation and GA. In circumstances where it is used to maintain GA by continuous IV infusion, the delta/alpha index could be used to control the syringe driver pump.

Medical Hypnosis and Conscious Sedation

Hypnosis can be a powerful agent in the treatment of many psychosomatic disorders such as irritable bowel syndrome and psychological complaints such as agoraphobia, anxiety states and phobias. It has been used to boost the immune response [10] and as an adjuvant in cancer therapy. A good book on hypnosis is [7]. However, the problem that has bedevilled hypnotherapy since Mesmer's time is the large variation in susceptibility to hypnotic suggestion within the population. Tests have been developed to assess susceptibility [12] but it is the contention of the authors that if it is deemed that the patient would benefit from hypnosis then a way should be found to improve the hypnotic response.

The general view is that it is not possible to assess depth of hypnosis without resort to eliciting hypnotic phenomena such as hand-arm levitation or compliance with test post-hypnotic suggestions. The clinical trial [4] comparing the EEG response in hypnosis with nitrous oxide conscious sedation (a technique familiar to dentists) showed that there was a good association between the hypnotic or sedated state and a strong alpha rhythm, and that resistance to hypnotic suggestion could be reduced by the nitrous oxide, and that both states could be regarded as altered states of consciousness. Once the patient had learned what to expect in deep relaxation this chemical sedation could be stopped.

The authors have used EEG monitoring routinely in a pain relief clinic for some years, administering nitrous oxide or, later, enflurane (a volatile inhalational anaesthetic agent)[5] as necessary. It is invaluable to be able to see if the patient is sufficiently relaxed and in an alpha state so that therapy is effective. Deeper hypnosis is associated with a lowering of the alpha frequency and appearance of theta waves, often as a double peak in the spectrum, the so-called alpha-theta state beloved by psychotherapists. Clearly the use of anaesthetic agents, however weak, should only be done in a hospital or dental surgery setting where resuscitation equipment is available, but a safe non-drug technique that shows great promise is the binaural beat method where EEG responses can be induced by pink noise fed to each ear. The phase differences of the two signals are caused to beat at the same frequency as the desired brain rhythm [1,2].

Benzodiazepines such as diazepam and other psychotropic drugs are notorious for undermining hypnotherapy efforts, possibly because of a reduction of the memory of the therapeutic suggestions, but often they can be detected by the level of beta activity of the EEG.

Sports Medicine

The value of psychological components contributing to success in many forms of sporting endeavour has come to prominence in recent years. Some are clear to the player and bystanders like the "yips" in golf – focal dystonia [9], and others are hidden but none the less important for peak performance. The "relaxed but focused" state or *zone* has been the subject of much research [6,8] but this has mainly been conducted under laboratory conditions. There seems to be a strong correlation of alpha activity with the *zone* and it was clear that the Bristol Process with its advantages over the FFT would be very suitable for players on the move.

A feasibility trial was carried out on some highly trained young athletes. Several sports were represented and all the participants showed that they were capable of getting into the *zone* of high alpha index while practising simulated competitive actions. For example, the Judo expert wore a baseball cap with electrodes around the rim. In spite of the large amount of movement, the alpha trend was clearly displayed and corresponded to peaks of focused concentration as shown below in Figure 8.

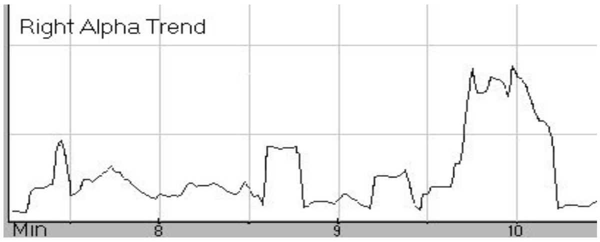

Figure 8: Alpha index trend of the Judo player

This illustrates that although it may be thought that player-initiated sports such as shooting, archery, golf, would be ideal for *zone* training, nevertheless player-reacting sports like judo, football, cricket probably have their own *zone* with high alpha content.

Reviewing EEG feedback with performance video recording promises to be a powerful training tool.

Summary and Future Developments

EEG analysis is a demanding application, particularly in "difficult" environments. We have been able to explore the use of an alternative process and found that it has opened up applications in sports science as well as in general medicine. There are a large number of potential applications for low cost, reliable, easy-to-interpret EEG monitors throughout medicine and "soft" medical applications such as relaxation, study, personal and arts performance/concentration improvement, self-administered psychological training (bio/neurofeedback), and sports performance. Clearly wireless units and easy to read scales of being "in the zone" would be an early requirement, especially for sports use in the field. It is to be hoped that future standards for minimal monitoring in anaesthesia will include EEG, and applications in Accident and Emergency and Intensive Care Units can be envisaged.

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