Electrode performance and signal processing strategies for the discrimination of EEG alpha waves: Implications for environmental control by unconstrained subjects without training

Andrew Searle
BE. (Hons) BSc.

Department of Applied Physics
of Technology, Sydney
Australia

A thesis submitted for the degree of Doctor of Philosophy

December 2000

CERTIFICATE OF AUTHORSHIP/ORIGINALITY

I certify that this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signature of Candidate

Production Note:
Signature removed prior to publication.

ACKNOWLEDGEMENTS

I would like to acknowledge the generous support, assistance and guidance that I have received from my supervisor, Assoc. Prof. Les Kirkup, and co-supervisor Prof. Ashley Craig; their efforts through the course of this thesis have been invaluable. I would also like to thank Mr. Geoff McCredie for help in the vacuum deposition laboratory, and Dr. Paul Swift for guidance on all things optical. I would also like to thank Amanda for many years of patience and understanding.

Contents

1 Introduction **1**
1.1 The electroencephalogram 2
1.1.1 The alpha EEG rhythm 2
1.2 Brain-computer interfaces . . . 5
1.2.1 Alpha EEG for environmental control. 8
1.3 Artifact sources in EEG 10
1.4 Objectives for this thesis 12
1.5 Structure of thesis 13

2 Methods for detection of alpha activity in the EEG **15**
2.1 Introduction..... 15
2.1.1 Conventional methodologies for alpha wave detection 16
The Percent Time and Integration alpha measurement methods . . . 16
Other methods 18
2.1.2 Alpha as a control mechanism . . . 20
2.1.3 Alpha EEG detection and artifacts 22
2.1.4 Scope of alpha wave detection study 23
2.2 Data Collection 23
2.2.1 EEG recording procedure 24
2.3 The Integration method 27
2.3.1 Implementation..... 28
2.3.2 A note on algorithm implementation 29
2.3.3 Threshold determination 30
2.3.4 Interpretation of results 30
2.3.5 An alternative method of comparing results 35
2.3.6 Combinations of electrode pairs 36
2.3.7 An extension to reduce the influence of false positive results 40
2.4 The Percent Time method 43
2.4.1 Distributions of peak EEG amplitudes 43

2.4.2 Percent Time implementation 46
2.4.3 Results..... 46
2.5 The Peak Counting method . 48
2.5.1 Results . 49
2.6 A comparison of results and discussion 52

3 Multi-electrode methods for alpha EEG detection 57
3.1 Introduction..... 57
3.2 Array sensor processing. 58
3.2.1 Representation of signals impinging on sensor arrays 59
Propagation speed of alpha waves 61
3.2.2 The Uniform Linear Array (ULA) 62
3.3 Beamforming 64
3.3.1 The Bartlett, or Conventional, beamformer . 65
3.3.2 Results from the application of a Bartlett beamformer 66
Spatial resolution of beamformers 68
3.3.3 Capon's beamformer 70
Design of an example Capon beamformer using simulated data. 73
3.3.4 Results using Capon beamformers 74
3.4 LCMV Filtering using the forward solution to EEG 76
3.4.1 Electrically modeling the head. 76
The suitability of the sphere-type head models 80
Incorporating the head model in a LCMV filter 82
3.4.2 Results using the LCMV filter. . . . 84
3.5 Adaptive filtering using an artifact reference 86
3.5.1 Introduction..... 86
3.5.2 The adaptive filter algorithm 88
3.5.3 Results from the application of the adaptive filter algorithm 91
3.6 Blind Source Separation 93
3.6.1 Introduction... 94
3.6.2 Theory..... 95
3.6.3 Selection of ICA algorithm . 98
How gaussian are the signals in EEG? . 98
Preprocessing 100
The Extended ICA Algorithm . . 100
The Fixed Point Algorithm. . . . 101
Comparison of the two algorithms 102
3.6.4 Results obtained for ICA analysis 111
3.7 A Comparison of results and discussion 113

4 Location-based methods for alpha EEG detection 117
4.1 Introduction 117
4.2 Source localisation using a Bartlett beamformer 118
4.2.1 Using a Bartlett beamformer for alpha EEG detection 120
4.2.2 Application of a sliding window averager 122
4.2.3 Results using Bartlett beamformer localisation. 123
4.3 Minimum variance beamformer for source localisation 124
4.4 MUSIC 125
4.4.1 Signal and noise subspaces 126
4.4.2 The MUSIC algorithm 128
4.4.3 EEG data and the MUSIC algorithm 129
4.4.4 Results 132
4.5 Use of the LCMV forward solution for source localisation 133
4.5.1 Example of source localisation. 135
4.5.2 The influence of the data block size 138
4.5.3 Examples of localisation 140
4.5.4 Results for alpha EEG detection using localisation with the four sphere head model 141
4.6 Localisation using the power source location coefficient 142
4.6.1 Results using the power source location method 145
4.6.2 A simplification of the power source method 145
4.7 A comparison of results and discussion 146
4.8 Discussion of alpha EEG detection techniques 148

5 Electrodes for biosignal sensing applications 154
5.1 Introduction 154
5.1.1 Historical background 155
5.2 Wet electrodes. 157
5.2.1 The electrode/electrolyte interface. 157
Overpotentials and electrode polarisation 159
5.2.2 Silver/silver chloride 160
5.2.3 Wet electrode impedance. 161
5.2.4 Limitations of wet and Ag/AgCI electrodes. 166
5.3 Dry electrodes. 169
5.3.1 Usage 169
5.3.2 Dry electrode impedance. 170
5.3.3 Limitations of dry electrodes. 170
5.4 Insulated electrodes. 171
5.4.1 Usage 171
5.4.2 Insulated electrode impedance 173
5.4.3 Limitations of insulated electrodes 174

5.5 Miscellaneous electrode structures 175
5.5.1 NASICON ceramic 175
5.5.2 Balsa. 176
5.6 Conclusion . 176

6 Skin/electrode impedance: characteristics and a new measurement method 179
6.1 Introduction..... 179
6.2 The electrical properties of skin 180
6.2.1 Nonlinearity..... 186
6.3 Impedance and signal fidelity . 187
6.3.1 Active impedance conversion. 189
FET buffers 191
Operational amplifier buffers 192
Using buffers with insulating electrodes 193
6.4 Techniques for the measurement of the skin/electrode impedance 195
6.4.1 Electrode configurations 196
Two electrode configuration 196
Four electrode configuration 197
Three electrode configuration. 197
Multiple electrodes 197
6.4.2 Impedance measurement techniques. 198
Impedance bridges 198
Phasemeters 200
Lissajous' figures 201
Active impedance conversion 202
Quadrature techniques . . . 203
Step input and square wave applications 204
6.4.3 Multifrequency measurement techniques 205
Fourier analysis 205
Commercial spectrum analysers 207
6.5 A new method for impedance plots 208
6.5.1 Introduction..... 209
6.5.2 Description of system. 211
Frequency determination 213
Calibration. 215
Acquisition. 216
6.5.3 Results..... 217
Application of system to skin/electrode impedance measurements 219

6.6 The relationship between contact impedance and powerline interference, revisited 221
6.6.1 Conclusion..... 224

7 A Comparison of electrode types for biosignal sensing 226
7.1 Introduction..... 226
7.1.1 Background..... 227
7.2 Silicon as a substrate for insulating electrodes 230
7.2.1 Thermal growth of silicon dioxide . . . 231
7.2.2 Thin film thickness determination using optical spectroscopy 233
Results. 236
7.2.3 Metal-semiconductor heterojunctions 238
Rectifying contacts 238
7.2.4 Ohmic contacts 240
7.3 A comparison of wet, dry and insulating electrode types. 243
7.3.1 Temporal dependence of contact impedance 244
Experiment 244
Results 246
7.3.2 Charge sensitivity of electrodes 248
Experiment 248
Results 250
7.3.3 Effect of electrode movement. 251
Experiment 251
Results 252
7.3.4 Discussion..... 255
7.4 Example data for bioelectric recording 257
7.5 Conclusion..... 261

8 Summary, conclusions and suggestions for further work 264

A Published or presented work based on research described in this thesis 271

B The International 10-20 System of EEG Electrode Placement 273

C Calculation of electrode positions on headband 275

D Mathematical definitions 278
D.1 Matrix rank 278
D.2 Singular Value Decomposition (SVD) 279

D.3 The pseudoinverse 279
D.3.1 Example 1: A non-singular matrix 280
D.3.2 Example 2: A singular matrix . . . 280
D.4 Cholesky decomposition 281
D.5 Numerical evaluation of Legendre and Associated Legendre polynomials 282
D.6 The Hilbert transformer 282
D.7 Equivalence of constant phase element model and empirical formula 284
D.8 Equivalence of frequency dependent component model and constant phase element model 285
D.9 Derivation of equations used for equal frequency spacing in impedance measurements 286

E FET devices 288
E.1 Introduction to FET types 288
E.1.1 Simple follower 289
E.1.2 Active loads 290

F Reflectance measurement using a spectrophotometer 291

G Short derivation of reflectance for a single layer film 293

List of Figures

2.1 Positions of the 19 electrodes on the head band 24
2.2 Frequency spectra for eyes open and eyes closed 26
2.3 EEG spectra showing eyes open, eye closure, jaw clenching, head movement and talking 27
2.4 Schematic diagram of the analogue alpha detection system 28
2.5 Frequency response for the 512 tap FIR bandpass filter. . 29
2.6 Example of the output from the integration method 31
2.7 Detection times a using the integration algorithm 33
2.8 Errors experienced using the integration algorithm, and RMS-only algorithm. 34
2.9 $\overline{\chi}$ values for the integration and RMS-only methods 36

2.10 Results for all combinations of electrodes . . 37
2.11 Best and worst performing electrode pairs . 38
2.12 Operation of the artifact rejection algorithm 42
2.13 Results obtained when using the artifact rejection algorithm 43
2.14 Probability distribution functions of alpha EEG maxima 44
2.15 Periods between rectified EEG maxima. . . 45
2.16 The process for percent time alpha method. 47
2.17 Results for Percent Time calculation method 48
2.18 Results for Peak Counting method, with EO threshold 49
2.19 Results for Peak Counting method, with two EC thresholds. 51
2.20 Results for Peak Counting method, with one EC threshold 52

3.1 Array sensor model 60
3.2 The Uniform Linear Array. 62
3.3 Effect of array size on the response for aULA 63
3.4 Using a coefficient array to steer gain 64
3.5 The response of an example Bartlett beamformer 66
3.6 Results obtained by applying a Bartlett beamformer to EEG data 68
3.7 Gain of four different Bartlett beamformers. 69
3.8 The response of an example Capon beamformer 73
3.9 Results obtained by applying a Capon beamformer to EEG data 75
3.10 Lines of electric potential from a dipolar source . . . **77**
3.11 Four-sphere model for the head 78
3.12 Potential at an electrode on the scalp due to dipoles. 81
3.13 Results obtained by applying the head model to EEG data 85
3.14 Functional diagram for an adaptive filter . . . 87
3.15 A demonstration of adaptive filter operation 88
3.16 Examples of signals applied to adaptive filters 90
3.17 Results obtained by applying EEG data to an adaptive filter 92
3.18 Comparison of results when data is applied to adaptive filter 93
3.19 Probability density functions of signal amplitudes 98
3.20 Segment of the EEG data collected using headband 104
3.21 Independent Components separated using fixed point ICA 105
3.22 Independent Components separated using extended ICA. 106
3.23 Independent Components projected onto electrode sites.. 107
3.24 Average alpha spectral power for each of independent components 108
3.25 Comparison of performance of ICA algorithms 110
3.26 Results obtained using ICA components '" 112

4.1 Example of Bartlett beamformer source localisation 119
4.2 Localisation using a Bartlett beamformer applied to illustrative EEG data. 119
4.3 Results for alpha EEG detection using Bartlett localisation. 122
4.4 Results for alpha EEG detection using Bartlett localisation . 123
4.5 Example of source localisation using Capon's beamformer .. 125
4.6 Localisation using Capon's beamformer with EEG data . . . 126
4.7 Comparison of the Bartlett beamformer, minimum variance beamformer and MUSIC source localisation algorithms 130
4.8 Localisation using a music beamformer 131
4.9 Gradient values after applying the MUSIC algorithm 132
4.10 Results for MUSIC algorithm on EEG data .. 133
4.11 Results from LCMV source localisation 136
4.12 Procedure to find the centre-of-gravity (COG) 137
4.13 Histograms of estimated *COG* values 139
4.14 Example of localisation using the head model 140
4.15 Results obtained using the four sphere head model for source localisation . 141
4.16 Graphical example of the power source localisation technique 143
4.17 The y component of the location coefficient (d_y) for example EEG data sets 144
4.18 Results after applying power source localisation to EEG data 145
4.19 Results after applying simplified power source localisation to EEG data . 146
4.20 Results for the best alpha EEG detection techniques discussed in Chapters 2 - 4 150

5.1 Einthoven's electrocardiograph. 156
5.2 Reactions at an electrode/electrolyte interface, and Stern's model . 158
5.3 Model for electrode/electrolyte interface . 163
5.4 Plots for the electrode/electrolyte interface impedance 164
5.5 Photosensitivity of silver/silver chloride electrodes 167
5.6 NASICON electrode construction . 175

6.1 **(a)** Skin Structure and **(b)** Major impedance areas in skin measurements as seen by two surface electrodes. 180
6.2 Impedance locus for skin 181
6.3 Simple 'three component' skin electrical model . 182
6.4 **(a)** Skin impedance model using constant phase element and **(b)** Impedance locus for a constant phase element only . . . 183

6.5 Frequency dependent impedance models 186
6.6 FET input active buffer 191
6.7 Operational amplifier buffer 192
6.8 Combination of electrode capacitance and input impedance forming a high pass filter 193
6.9 Two and four electrode configuration . . 196
6.10 Bridge impedance measurement circuits. 199
6.11 An example of a Lissajous' Diagram. . . 201
6.12 Active impedance converter 203
6.13 Spectra for square and sawtooth waveforms 205
6.14 The effect of swept impedance readings . . . 210
6.15 Physical layout of impedance spectroscopy system. 211
6.16 Impedance conversion circuit 212
6.17 Theoretical impedance values of the three component model 214
6.18 Impedance values for tests on parallel RC combination . . . 217
6.19 Comparison between coefficient of variation of power spectra for arbitrary and square waveform methods. 218
6.20 Variation over time of impedance locus 219
6.21 Variation over time of impedance values 219
6.22 Variation of impedance locus for Ag/AgCI electrodes 221
6.23 Interference performance of stainless steel electrodes. 222
6.24 Impedance values for Ag/AgCI electrodes applied to forearm 224

7.1 Reflectance for a single layer film on substrate 234
7.2 Data for *n* of silicon (raw data from Palik (1985)) 236
7.3 Experimental data and best fits for reflectance spectra 237
7.4 The metal and semiconductor joins 239
7.5 Ohmic heterojunction. 241
7.6 A pseudo-ohmic tunneling heterojunction . 241
7.7 Location on the forearm of wet electrodes, and of the assembly containing the three dry electrode pairs 245
7.8 Operation of multiplexing device . 246
7.9 Contact impedance vs time for four electrode pairs 247
7.10 Contact impedance vs time for four electrode types 247
7.11 Experimental arrangement for charge sensitivity tests 249
7.12 RMS interference resulting from a moving, charged rotor 251
7.13 Experimental arrangement for movement artifact tests 252
7.14 Artifact caused by vibration of three electrodes types . 253
7.15 EeG recordings for wet, dry and insulating electrodes. 258

B.1 The International 10-20 System of EEG Electrode Placement 274

C.1 Positions of electrodes on the head band . 277

D,l Real and imaginary parts of original signal 283
D.2 Imaginary part of FFT for input signal, and vector *b* 283
D.3 Real and imaginary parts of signal after Hilbert transform. 284
D.4 Simple 'three component' skin electrical model. 286
D.5 Impedance locus for skin 286

E.1 n-type FETS 289
E.2 JFET Source Follower 290

F.1 Measurement stage of the spectrophotometer . 292

G.1 Reflectance for a single layer film on substrate 293

List of Tables

1.1 Spectral components of the EEG 2

2.1 Ranking of alpha detection methods introduced in Chapter 2 54

3.1 Mathematical notation for sensor array processing . 60
3.2 Dimensions used in previous studies for head model 80
3.3 Comparison of two ICA algorithms 103
3.4 Ranking of alpha detection methods introduced in Chapter 3 114

4.1 Averaging window sizes. 123
4.2 Ranking'of alpha detection methods introduced in Chapter 4 147
4.3 Ranking of the best results from all detection techniques discussed 151
4.4 Processing time for alpha EEG detection methods 151

5.1 Electrode half cell potentials. 159
5.2 Insulating materials used in bioelectric measurements 172
5.3 Comparison of Electrode Types 177

6.1 Powerline interference from three electrode pairs. 188

7.1 Summary of dry and insulating electrode literature 229

C.1 Mean and standard deviation of head sizes surveyed. 275

ABSTRACT

The phenomenon of the increase in alpha EEG activity associated with eye closure has been shown to be successful for implementing environmental control for disabled persons. Studies in this thesis investigate strategies which improve the reliability, robustness, and ease of use of alpha EEG control systems. Primarily, research covers the effectiveness of alpha EEG detection algorithms (with regard to detection time and susceptibility to artifact) and the construction and use of EEG sensing electrodes.

Many new techniques for the detection of the increase of alpha EEG associated with closure are researched, developed, implemented and evaluated. All detection techniques are compared to a conventional method using a novel performance parameterisation criterion. In conjunction with the application of the same EEG data sets to all techniques, the use of the performance criteria enables a fair and quantitative comparison to be made between alpha detection methodologies. Detection techniques employed include enhanced versions of conventional methods, localisation of apparent alpha sources in the brain, and preprocessing methods (such as spatial filtering, adaptive filtering and independent component analysis). The best performance of alpha EEG detection was given by the source power alpha localisation technique, which showed statistically significant and practically important improvements in performance over conventional techniques. Additionally, this localisation technique is convenient and fast to implement.

In situations in which electrodes are intended for unsupervised use with environmental control systems, the evaluation of alternative types to the conventional wet electrodes is required, as the use of wet electrodes has several drawbacks. The performance of wet, dry and insulating electrodes is compared in this research. One aspect of the quantitative comparison of electrodes types is the measurement of contact impedance. To enable the fast and accurate measurement of impedance spectra, a new impedance spectroscopy system was developed as part of this thesis. In addition to comparison of impedance criteria, electrodes were evaluated in the presence movement-based, and electric field induced, artifacts. The electrode comparisons were carried out in a direct and quantitative manner in a controlled test environment for the first time. Results indicate that, in contrast to earlier reports, both dry and insulating electrode perform well with respect to artifact and offer a viable alternative to wet electrodes for long-term monitoring of biosignals from the surface of the skin. More improvements are required before such electrodes are suitable for EEG usage.