

**A NEW APPROACH TO THE
ANALYSIS OF THE THIRD HEART SOUND**

A thesis completing the requirements for
the degree of

MASTER OF SCIENCE

in

The Department of Applied Mathematics,
The University of Adelaide, South Australia.

by

Gary John Ewing, B.App.Sc.(Biophysics)

October 1988

ERRATA

Chapter 3

On page 32 insert "bands" after "15 Hz energy" in section 3.4.

Chapter 4

Page 45 section 4.3 : The sequence " $\{y_1, y_2, \dots, y_{M+N-1}\}$ " should read " $\{y_1, y_2, \dots, y_{M+N-1}\}$ "

The following equations are ammended as follows:

Equation 4.74 on page 56 is ammended to:

$$\begin{bmatrix} R_{xx}(0) & R_{xx}(-1) & \dots & R_{xx}(1-M) \\ R_{xx}(1) & R_{xx}(0) & \dots & R_{xx}(2-M) \\ \vdots & & & \vdots \\ R_{xx}(M-1) & R_{xx}(M-2) & \dots & R_{xx}(0) \end{bmatrix} \begin{bmatrix} a_{M-1}^{(M-1)*} \\ \vdots \\ a_1^{(M-1)*} \\ 1 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ P_M \end{bmatrix} \quad (4.74)$$

Equation 4.76 on page 56 is ammended to:

$$\begin{bmatrix} R_{xx}(0) & R_{xx}(-1) & \dots & R_{xx}(-M) \\ R_{xx}(1) & R_{xx}(0) & \dots & R_{xx}(1-M) \\ \vdots & & & \vdots \\ R_{xx}(M) & R_{xx}(M-1) & \dots & R_{xx}(0) \end{bmatrix} \left\{ \begin{bmatrix} 1 \\ a_1^{M-1} \\ \vdots \\ a_{M-1}^{M-1} \\ 0 \end{bmatrix} + \rho_M \begin{bmatrix} 0 \\ a_{M-1}^{(M-1)*} \\ \vdots \\ a_1^{M-1} \\ 1 \end{bmatrix} \right\}$$

$$= \begin{bmatrix} P_{M-1} \\ 0 \\ \vdots \\ \Delta_M^* \end{bmatrix} + \rho_M \begin{bmatrix} \Delta_M^* \\ 0 \\ \vdots \\ P_{M-1} \end{bmatrix} \quad (4.76)$$

Equation 4.78 on page 57 is ammended to:

$$\begin{bmatrix} R_{xx}(0) & R_{xx}(-1) & \dots & R_{xx}(-M) \\ R_{xx}(1) & R_{xx}(0) & \dots & R_{xx}(1-M) \\ \vdots & & & \vdots \\ R_{xx}(M) & R_{xx}(M-1) & \dots & R_{xx}(0) \end{bmatrix} \begin{bmatrix} 1 \\ a_1^M \\ \vdots \\ a_M^M \end{bmatrix} = \begin{bmatrix} P_M \\ 0 \\ \vdots \\ 0 \end{bmatrix} \quad (4.78)$$

chapter 6

Below equation 6.16 on page 86, replace "pole" with "complex pole" and "zero" with "complex zero".

Below equation 6.27 should read:

"where P = AR order, Q = MA order

c_k = cepstral coefficients

with $c_k = c_{AR} - c_{MA}$ "

In the diagram on page 89 :

"eqn 6.29" should read "eqn 6.28"

and "eqn 6.30" should read "eqn 6.29"

Contents

Declaration	vii
Acknowledgements	viii
Summary	ix
1 GENERAL INTRODUCTION	1
1.1 Basic Introduction to the Heart and the Heart Sounds.	1
1.2 Heart Sounds and The Cardiac Cycle.	2
1.2.1 First Heart Sound.	6
1.2.2 Second Heart Sound.	6
1.2.3 Third Heart Sound.	7
1.2.4 Fourth Heart Sound.	8
1.3 Diagnostic Implications of the Third Heart Sound.	8
1.4 Scope of the Research.	10
2 THE INSTRUMENTATION AND DATA COLLECTION	11
2.1 Phonocardiography an Extension of Auscultation.	11
2.2 Phonocardiogram Data Aquisition.	12
2.3 Data Storage.	15

2.4	Introduction to Echocardiography.	16
2.5	2-Dimensional Echocardiography.	20
2.6	Echocardiographic Measurements.	21
3	ANALYSIS OF THE THIRD HEART SOUND BY THE FAST FOURIER TRANSFORM METHOD.	28
3.1	The Fast Fourier Transform.	28
3.2	The Fast Fourier Transform in Heart Sound Analysis.	29
3.3	Derived Spectral Parameters.	32
3.4	Correlation of Spectral and Echocardiographic Data.	33
3.5	Discussion.	37
3.6	Limitations.	39
4	MAXIMUM ENTROPY SPECTRAL ANALYSIS	42
4.1	Entropy	44
4.2	Linear Digital Filtering	44
4.3	Weiner Filtering	46
4.3.1	Mean Square Error.	47
4.3.2	The Prediction Error Filter.	49
4.4	Maximum Entropy Spectral Analysis.	52
4.5	Algorithm to Solve the Prediction Error Filter Equations.	57
4.5.1	Order Selection.	60
4.5.2	Computational Load.	61
5	MAXIMUM ENTROPY SPECTRAL ANALYSIS OF THE THIRD HEART SOUND	64
5.1	Numerical Experiments with Synthetic Data.	65

5.1.1	Model Order Estimation.	65
5.1.2	Experiments with Synthetic Data.	67
5.2	Comparison of MEM and FFT Spectral Analysis of S3.	70
5.2.1	Signal Preprocessing.	70
5.2.2	Fourier Transform Method.	76
5.2.3	Maximum Entropy Method.	76
5.2.4	Comparison of the FFT MESA Techniques.	80
5.3	Correlation of MESA and Echocardiographic Data.	80
5.4	Discussion.	80
6	ARMA MODELLING: RECOMMENDATIONS FOR FURTHER WORK	83
6.1	Auto-regressive Moving Average (ARMA) Modelling.	84
6.2	ARMA Model From The Maximum Entropy (AR) Model.	85
6.2.1	Homomorphic Systems.	85
6.2.2	The Complex Cepstrum.	87
6.2.3	Maximum Entropy ARMA Spectral Estimate.	88
6.2.4	ARMA Spectrum from AR Coefficients.	90
6.3	Deconvolution of the Chest Wall Transfer Function from the The Third Heart Sound.	91
6.4	Conclusions and Recommendations for Further Work.	92
A	The Entropy of a Gaussian Sequence.	96
B	Theorem Due to Szëgo.	98
C	Spectral Factorization.	100

List of Figures

1.1	Functional diagram of the circulatory system.	3
1.2	Electrical activity of the Heart.	5
1.3	Relationship of the Heart Sounds to other cardiac events.	9
2.1	PCG Data Acquisition System	13
2.2	Lead ii ECG	14
2.3	Digitized ECG signal.	16
2.4	Digitized PCG signal.	18
2.5	Ultrasound Wave Propagation	18
2.6	Propagation, Reflection and Refraction of Ultrasound.	19
2.7	M-mode Echocardiogram	19
2.8	2-D Echocardiogram	24
2.9	Beam Steering	25
2.10	Long Axis View	26
2.11	Short axis view.	26
2.12	Apical two-chamber view.	27
2.13	Apical four-chamber view.	27
3.1	Process in obtaining FFT spectra.	30
3.2	A typical FFT spectrum.	31
3.3	Histogram of S3 energy spectral distribution.	35

4.1	Linear Digital Filter	46
4.2	Prediction Error Filter	51
4.3	MESA Algorithm	62
5.1	Flowchart for flattness testing.	66
5.2	Synthetic Data	68
5.3	FFT of Synthetic Data (10 Hz sinewave)	71
5.4	MESA of Synthetic Data (10 Hz sinewave)	71
5.5	FFT of Synthetic Data (10 Hz, 20 Hz and 40 Hz sinewaves).	72
5.6	MESA of Synthetic Data (10 Hz, 20 Hz and 40 Hz sinewaves).	72
5.7	Synthetic Data with Gaussian noise (SNR 80db)	73
5.8	Synthetic Data with Gaussian noise (SNR 65db)	73
5.9	Synthetic Data with Gaussian noise (SNR 60db)	74
5.10	Synthetic Data with Gaussian noise (SNR 40db)	74
5.11	Synthetic Data with Phase Jitter (1 %).	75
5.12	Synthetic Data with Phase Jitter (0.5 %).	75
5.13	FFT spectrum of the S3 of subject 11.	78
5.14	MESA spectrum of the S3 of subject 11.	78
5.15	Histogram of S3 energy vs Frequency	81
6.1	Canonic representation of some classes of homomorphic systems.	86
6.2	Canonic representation of multiplicative homomorphic systems.	94
6.3	Approach for finding ARMA coefficients.	95

List of Tables

3.1	Details of the subjects.	34
3.2	Position of window for S3 in cardiac cycle.	34
3.3	% energy per frequency band.	36
3.4	Echo & Phono Derived Parameters	36
3.5	Correlation coefficients for parameters vs freq bands	41
3.6	Correlation coefficients for age vs some parameters.	41
5.1	Freq peaks in the FFT spectra of S3	77
5.2	Details of subjects.	77
5.3	MESA peaks for all subjects.	79
5.4	Correlation coefficients.	79

Declaration

I declare that this thesis is a record of original work and that it contains no material which has been accepted for the award of any other degree or diploma in any University.

To the best of my knowledge and belief, this thesis contains no material previously published or written by any other person, except where due reference is given in the text of the thesis.

I consent to this thesis being made available for photocopying or loan.

Gary J. Ewing
1988

Acknowledgements

I wish to express thanks to my supervisor, Dr. J. Mazumdar who has lent the much needed encouragement.

I also wish to thank my friend and colleague Dr. N. Fazzalari (Nick) for his collaboration with respect to 2-D echocardiographic data collection, and our many discussions.

My thanks are also extended to Dr. E. Goldblatt and the Department of Cardiology of the Adelaide Children's Hospital for the extensive co-operation and assistance offered.

Last but not least my thanks go to Dr. E. Van vollenhoven of Leiden University, (The Netherlands), for his many useful comments and his presentation at European conferences of the results of this work.

The work of part of this thesis was supported by a grant from the Channel 10 Children's Medical Research Foundation of South Australia and an URG grant from the University of Adelaide.

Summary

There has been in the past and still is controversy over the genesis of the third heart sound (S3). Recent studies, strongly suggest that S3 is a manifestation of a sudden intrinsic limitation in the expansion of the left ventricle. The thesis has aimed to explore that hypothesis further using combined echocardiographic and spectral analysis techniques. Spectral analysis was carried out via conventional fast fourier transform methods and the maximum entropy method. The efficacy of these techniques, in relation to clinical and scientific application, was explored further. Briefly discussed was the application of autoregressive-moving average (ARMA) modelling for spectral analysis of S3, in relation to further work. Following is a brief synopsis of the thesis:

CHAPTER 1 This gives an historical and general introduction to heart sound analysis. Discussed briefly is the physiology of the heart and heart sounds and the diagnostic implications of S3 analysis.

CHAPTER 2 Here is discussed the instrumentation system used and phonocardiographic and echocardiographic data aquisition. Data preprocessing and storage is also covered.

CHAPTER 3 In this chapter the application of a FFT method and correlation of resultant spectral parameters with echocardiographic parameters is reported.

CHAPTER 4 The theoretical development of the maximum entropy technique (based on published papers and expanded) is discussed here. Numerical experiments with the method and associated problems are also discussed.

CHAPTER 5 The MEM is applied to the spectral analysis of S3 and compared with the FFT method. Correlation analysis of MEM derived spectral parameters with echocardiographic data is performed.

CHAPTER 6 Here ARMA modelling and application to further work is discussed. An ARMA model from the maxixum entropy coefficients is derived. The application of this model to the deconvolution of the chest wall transfer function is discussed as an approach for further work.