MUSIC INCORPORATING UTERINE CONTRACTION IN NON-INVASIVE FETAL HEARTBEAT DETECTION

Walid A. Zgallai

Faculty of Engineering Technology and Science,
Higher Colleges of Technology, UAE
walidzgallai@yahoo.co.uk

ABSTRACT

The aim of this paper is to detect fetal heart beats temporally overlapping with the transabdominally-measured QRS-complexes of the mother, non-invasively. Modified, Weighted and uterine contraction interference signal covariance matrix incorporated spectral MUSIC technique is applied. It is based on partitioning the subspace containing the ECG signal bearing the mother and fetal, and the orthogonal subspace containing the uterine contraction interference signal plus noise. This exploits the orthogonality between the signal and noise subspaces provided that the noise is additive white Gaussian. In the modified MUSIC, subsequent separation of the mother and fetal QRS-complexes is performed in their shared signal subspace.

KEYWORDS

Non-invasive, Fetal heartbeat detection, MUSIC Spectral estimation, uterine contraction, Weighted Kaiser filter.

1. INTRODUCTION

Difficult situations arise in which the maternal and fetal heart beats are commensurate. Episodes of near coincident maternal and fetal QRS-complexes have been found in about 10% of the transabdominal ECG data. In such episodes about every ten seconds a fetal heartbeat coincides with the maternal QRS-complex. This is similar to one problem which has often arisen in Radar applications [1] where two coincident targets have common temporal and spectral characteristics. Such a problem and others different in nature, e.g., Sonar, and underground buried objects, have been dealt with using the following spectral estimation methods that are based on partitioning the signal and noise subspaces; (i) the conventional multiple signal classification (MUSIC) method [2], (ii) the Pisarenko harmonic decomposition (PHD) method [3], (iii) the eigenvector (EV) method [4], and (iv) the minimum norm method [5]. Such subspace parameter or frequency estimation methods differ only in what part of the noise subspace they each use [6].

The maternal QRS-complex principal spectral peak is around 17 Hz, and the fetal QRS-complex principal spectral peak is around 30 Hz [7]. The spectral content can be used in the detection of either signal within the maternal cardiac cycle. A modified MUSIC algorithm has been devoted to identifying anomalous QRS-complexes and P-waves such as P-on-T-waves and P-on-QRS-complex episodes for adult patients in the frequency domain [7]. For fetal heart rate (FHR) detection in labour one has to overcome two problems; (i) poor spectral resolution, and (ii) the

David C. Wyld et al. (Eds) : CCSEA, CLOUD, DKMP, SEA, SIPRO - 2016
pp. 191–198, 2016. © CS & IT-CSCP 2016 DOI : 10.5121/csit.2016.60217

influence of the coexisting labour contraction signals [8] which exhibits a broad spectrum, and are characterised by having resonances, one of which is overlapping with the main fetal spike event. The fetal heartbeat detection is accomplished by thresholding the enhanced fetal spikes in the frequency domain. A challenge is to enhance the resolution of the mother and fetal QRS-complexes' principal pseudo-spectral peaks, (MPPP) and (FPPP), respectively, and to nudge the UCS plus noise into a separate subspace, the interference subspace (I-subspace), whereby orthogonalisation is forced between the I-subspace and the signal subspace (S-subspace) containing both the mother and / or the fetal QRS signature imprints. An auxiliary method based on *the* Gram-Schmidt orthogonalisation is employed in addition to Generalised Singular Value Decomposition (GSVD) which deals with partitioning signal and coloured noise subspaces [9]. This technique deals with the UCS during the strong peaks of labour contractions which have noise-like characteristics and are heavily contaminated with other noise artefact. The paper is organised as follows; Methodology is described in section 2. Results are shown in Section 3. Discussion is presented in Section 4. Conclusions are summarized in section V.

2. METHODOLOGY

Each maternal cardiac cycle has been divided into four segments of 250 msec each. The segmentation starts 50 msec before the maternal R-wave and continues until the end of the first segment. The other three equal segments are adjusted according to the maternal heart rate. There are inevitable deviations in the 17 Hz and the 30 Hz of the mother and fetal QRS-complex pseudo-spectra, respectively. Five overlapping and optimised Kaiser windows have been used in the detection of the MPPPs; 15-19 Hz. Ten overlapping and optimised Kaiser weighted windows have been used in the detection of the FPPPs; 28-38 Hz. The optimised Kaiser weights have been given in [10]. The model order has to be chosen carefully. The optimum model order is found by trial and error to be eleven for the signal and four for the noise. The method is not sensitive to small deviations in the model order.

The spectrum of the UCS may include comparatively strong narrowband spectral components centred around 5 Hz, 30 Hz, 45 Hz, 60 Hz, and 90 Hz in addition to some broadband components [10]. The uterine contraction component at 30 Hz masks the FPPP. A challenge is isolating the FPPP at 30 Hz in the presence of the UCS peak at the same frequency. Using a new pseudo-spectral localiser which incorporates the modified covariance matrix representing the UCS plus coexisting noise artefact, and seeks to reduce the influence of background uterine activities in the pseudo-spectral MUSIC localisation procedure by partitioning the two subspaces; one contains the desired signal parameters and the other contains the UCS parameters, is proposed. An accurate estimate of the UCS modified covariance matrix is needed to be incorporated in the pseudo-spectral localiser. A portion of the data that contains only noise fields, and does not contain any signal information such as the P-waves or the QRS-complexes, is utilised. When such a segment of the data, that is P-wave- and QRS-complex-free, is sufficiently long for the MUSIC pseudo-spectral localiser, an accurate estimate of the UCS modified covariance matrix can be obtained.

The mathematical formulation is based on [4, 10]. A flowchart is given in [10]. The temporal window is restricted to 250 msec. The Kaiser filter weights are applied to each of the 250 msec windows and the weights are optimised to enhance the principal peaks of either QRS-complex in their respective temporal domains. The data portions earmarked for the I_{noise} are segments that are free from mother and fetal QRS-complexes.

To exploit a MUSIC methodology [5] which incorporates a tailor-made subspace fitting for individual QRS spectral signatures based on *a priori* information, if we ignore the influence of the uterine contraction interference signals, the technique is based on weighting the covariance matrix of the transabdominally-measured signals, which in turn uniquely modifies the signal and noise subspaces to enhance and retain only eigenvectors that result in the MPPP at 17 Hz, or the FPPP at 30 Hz. In the absence of uterine contraction interference signals and assuming white Gaussian noise presence, this is a weighted MUSIC technique. The signal and noise subspaces will be reconfigured by two tailor-made weighting Kaiser functions, one is aimed at enhancing the maternal QRS spectral peak and the other is aimed at enhancing the fetal QRS spectral peak.

3. RESULTS

The proposed localiser is applied to segments of the trnasabdominally-measured maternal ECG signal. Linearisation of the data is employed [11]. The UCS modified covariance matrix is calculated using the data portion in the segments that are maternal and fetal event free. Fig. 1 shows the results using the sequentially optimised, weighted MUSIC with and without the incorporation of the UCS modified covariance matrix for the case of maternal and fetal R-wave separation of 9 msec. Fig. 1 (a) depicts superimposed and synchronised maternal transabdominal and fetal scalp ECGs with maternal R-wave to fetal R-wave separation of 9 msec, respectively. Fig. 1 (b) shows the results employing the Modified MUSIC without UCS incorporation. The maternal MPPP is at 17 Hz, shown at the left hand part of the figure, the FPPP of the first fetal heartbeat is shifted at 31 Hz, shown in the inset at the right hand part of the figure. Fig. 1 (c) depicts the results of the Weighted and $\mathbf{I}_{noise}$ incorporated spectral MUSIC for the transabdominally-measured ECG signal. The fetal FPP is stronger and sharper around 31 Hz, and there is significant noise reduction in the QRS-free segments [7].

The effect of proximity of the maternal and fetal R-waves on the frequency deviation of the FPPP around 30 Hz, and on the fetal heart detection rate, in all observed cases of coincident mother and fetal QRS-complexes has been studied. The proposed algorithm has been applied to approximately 50,000 maternal cardiac cycles, including 4,873 coincident QRS-complexes cases. The results are shown in Table 1.

TABLE 1: The effect of proximity of the maternal and fetal R-wave on the frequency deviation of the FPPP at 30 Hz, and on the fetal detection rate.

R_m-R_f separation	40 msec	35 msec	25 msec	20 msec	15 msec	7 msec	0 msec
Frequency deviation ±	1.73 Hz	1.92 Hz	2.09 Hz	2.17 Hz	2.31 Hz	2.52 Hz	2.74 Hz
Overlapping windows	5	5	5	5	8	9	10
Detection rate (%)	93.81	93.63	93.56	93.49	93.24	92.35	91.83

From the overall results, it is observed that;

1. For a fixed model order of 11 and 4 for the signal and noise subspaces, respectively, the algorithm is capable of detecting fetal heartbeats, at a rate of 92%, when the mother and fetal R-waves are synchronised, provided that appropriate sequential weightings for the mother and the fetal are maintained throughout. As the separation between the mother and fetal R-waves is increased, there is a slight increase in the corresponding detection rate and a decrease in the FPPP frequency deviations.

2. The incorporation of the covariance matrix of the UCS helps to strengthen and sharpen the FPPPs in some cases and hence improves the resolution, and reduces the sensitivity of the FPPPs to small deviations from the optimal model order.

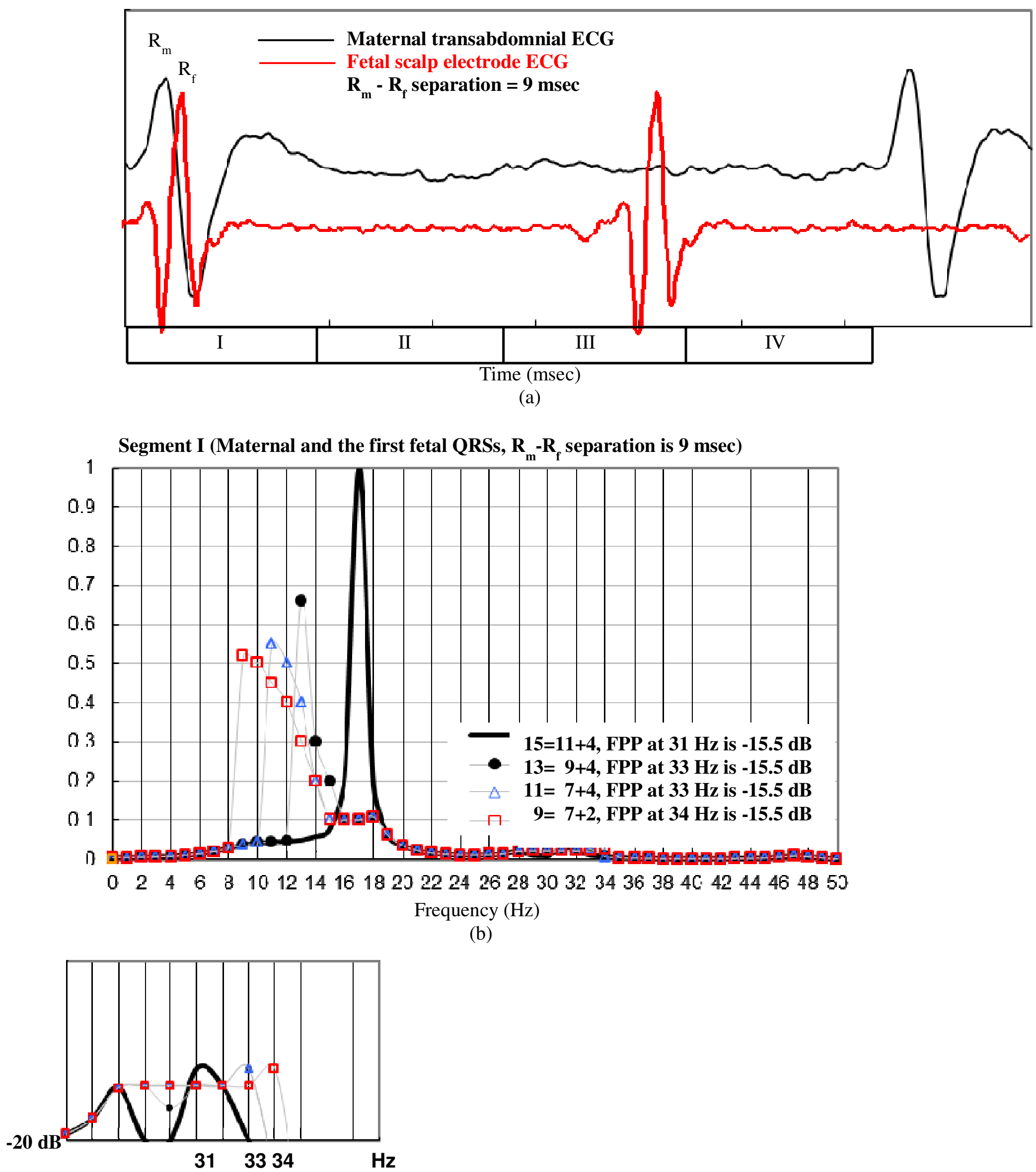
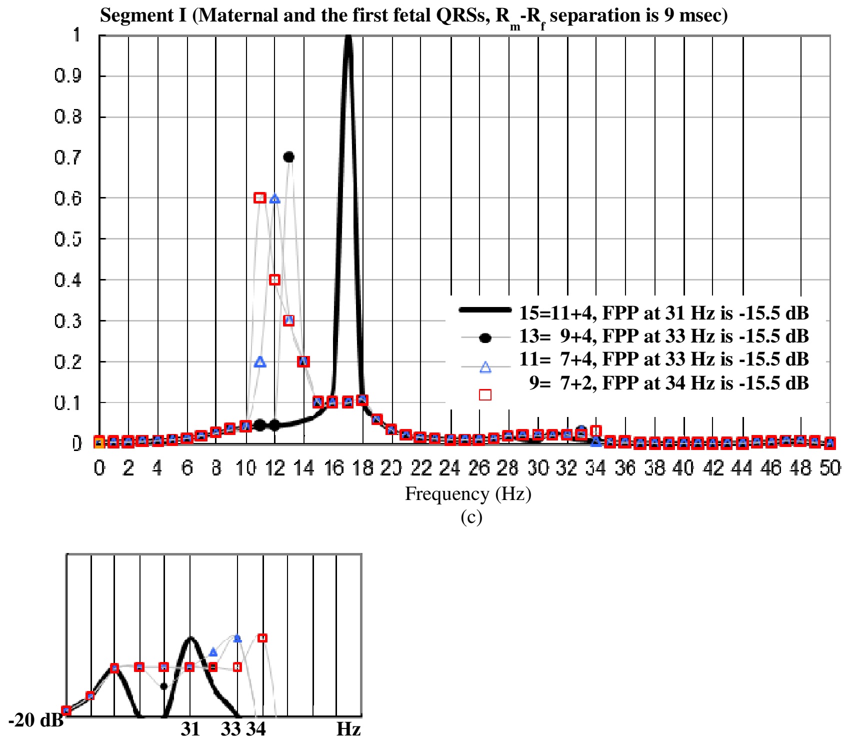


Figure 1. (a) Superimposed and synchronised maternal transabdominal and fetal scalp ECGs with maternal R-wave to fetal R-wave separation of 9 msec. The maternal cardiac cycle begins 50 msec before the R-wave and ends 50 msec before the next R-wave. The subject is at the first stage of labour, 40 weeks gestation. The maternal cycle has 500 samples at a sampling rate of 0.5 KHz. Segment I: maternal QRS-complex, segment II: the first fetal heartbeat with maternal contribution, segment III: QRS-free ECG, and segment IV: the second fetal heartbeat with maternal contribution. (b) Weighted spectral MUSIC for segment I of the transabdominally-measured ECG signal. As a result of close proximity, the FPP tends to broaden. Also, the FPP exhibits increased sensitivity to small deviations from the optimal model order in segment I. (c) Weighted and $\mathbf{I}_{noise}$ incorporated spectral MUSIC of segment I. Insets (right) show the FPPPs in dB.



(c)

Figure 1. (continued) (a) Superimposed and synchronised maternal transabdominal and fetal scalp ECGs with maternal R-wave to fetal R-wave separation of 9 msec. The maternal cardiac cycle begins 50 msec before the R-wave and ends 50 msec before the next R-wave. The subject is at the first stage of labour, 40 weeks gestation. The maternal cycle has 500 samples at a sampling rate of 0.5 KHz. Segment I: maternal QRS-complex, segment II: the first fetal heartbeat with maternal contribution, segment III: QRS-free ECG, and segment IV: the second fetal heartbeat with maternal contribution. (b) Weighted spectral MUSIC for segment I of the transabdominally-measured ECG signal. As a result of close proximity, the FPP tends to broaden. Also, the FPP exhibits increased sensitivity to small deviations from the optimal model order in segment I. (c) Weighted and $\mathbf{I}_{noise}$ incorporated spectral MUSIC of segment I. Insets (right) show the FPPPs in dB.

3. The modified MUSIC without UCS incorporation has resulted in the following fetal heart detection rates: (i) 89.23%, 97.51%, and 91.20% for coincident, non-coincident mother and fetal QRS-complexes, and overall average, respectively. The Weighted and $\mathbf{I}_{noise}$ incorporated spectral MUSIC has resulted in the following fetal heart detection rates: (i) 93.52%, 99.35%, and 95.50% for coincident, non-coincident mother and fetal QRS-complexes, and overall average, respectively. The results have been verified by the recording of the instantaneous scalp fetal heart rate, measured when deemed necessary by the doctor on call after consent is obtained.

To calculate the bias, the expected values of the estimates are those obtained using the 250 msec segments from the maternal transabdominal ECG signal for a predominantly maternal QRS segment and a fetal heartbeat with maternal contribution. Those true values and estimates were calculated for 1000 segments. The results are 1.23 and 2.15 for MPPPs and FPPPs, respectively. For the maternal and fetal QRS-complex, the more deviation of the detected frequency of the MPPP around 17 Hz and the FPPP around 30 Hz, respectively, from the respective actual frequency, the higher the bias will be. The variance range is 0–8, with an average of 4.127, when calculated for 120,000 FHBs.

4. DISCUSSION

Assuming a maternal heart rate of 60 bpm yields a cardiac cycle length of 1000 msec. Each maternal cardiac cycle has been divided into four equal segments of 250 msec. The average rate by which the first fetal event coincides with the QRS-complex of the mother is 9.8%, based on 50,000 maternal cardiac cycles. When the two QRS-complexes of the mother and fetal coincide in segment I, segment II is usually free from such events and may be taken as the UCS plus noise artefact segment. On average, the second fetal heartbeat occurs in segment III. And if there is a third fetal heartbeat, then it is likely to occur over both the fourth segment of the present cycle and the first segment of the next cycle. In most cases, two fetal heartbeat occurrences within each maternal cardiac cycle were encountered, even when the maternal heart rate goes up during labour contractions. The deceleration of the fetal heart rate after the peak of labour contractions is normal and not proven to be related to the maternal heartbeat as her heart will still be racing for a while after the peak of contractions.

Successful detection of coincident mother and fetal QRS-complexes has resulted in an increase of 9.3% and 5.4% over and above the cumulants [12] and the bispectrum [13] template matching techniques, respectively. The mother and fetal QRS-complexes coincide making it difficult to separate them using any time-domain technique. With the cumulants method [12] there is a 13.8% failure rate, partially due to 9.8% rate of QRS-complex coincidences, and the rest, 4% rate, is due to overlapping fetal QRS-complex and maternal T-wave. The bispectrum method [13] failure rate of 9.8% is purely due to QRS-complex coincidences as there is a shortcoming in acquiring sufficiently high resolution to separate the bispectral peaks of the mother and fetal QRS-complexes. The overlapping of the fetal QRSs and the maternal T-waves can be resolved by the bispectrum template matching technique. The above percentages of QRS-complex coincident episodes have been found in the 50,000 maternal heartbeat database. The alternative is to try to resolve them in the frequency-domain [14-15].

5. CONCLUSIONS

This paper proposed a modified, Weighted and $\mathbf{I}_{noise}$ incorporated spectral MUSIC technique to detect temporally overlapping fetal heartbeats with maternal QRS complexes from transabdominal measurements, with the fetal scalp as a reference when deemed necessary, during temporally and spectrally overlapping uterine contractions. Performance analysis showed increased rate of detection for the Weighted and $\mathbf{I}_{noise}$ incorporated spectral MUSIC over and above that achieved employing the weighted spectral MUSIC.

The incorporation of the covariance matrix of the UCS helps to strengthen and sharpen the FPPPs for the optimum model order and in some cases it appears to be tolerant to a change in the model order from 11 and 4 to 9 and 4 for the signal and noise subspace, respectively. It has also resulted in a significant noise artefact reduction in the QRS-free segments. The method has resulted in the following fetal heart detection rates: (i) 93.52% for coincident mother and fetal QRS-complexes, (ii) 99.35% for non-coincident mother and fetal QRS-complexes, and (iii) 95.50% overall average. Without the incorporation of the UCS modified covariance matrix into the mathematical formulation of the sequentially optimised, weighted MUSIC, the following fetal heart detection rates have been obtained: (i) 89.23% as opposed to the 93.52% for coincident mother and fetal QRS-complexes, (ii) 97.51% as opposed to the 99.35% for non-coincident mother and fetal QRS-complexes, because in the former no appropriate noise model was assumed in the analysis, and (iii) 91.20% overall average.

REFERENCES

[1] S. Haykin, A. Steinhardt, "Adaptive Radar detection and estimation," A volume in the WileySeries in Remote Sensing, J. A. Kong, Series Editor, J. Wiley and Sons, Inc., 1992.

[2] R. Schmidt, "Multiple emitter location and signal parameter estimation," Proceedings RADC Spectrum Estimation Workshop, pp. 243-258, 1979.

[3] V. F. Pisarenko, "The retrieval of harmonics from a covariance function," Geophysics Journal Royal Astronomy Society, Vol. 33, pp. 347-366, 1973.

[4] S. Haykin, Adaptive filter theory, Prentice Hall, 1991.

[5] S. Marple, Spectral Analysis With Applications, Prentice Hall, 1987.

[6] S. Kay, Modern Spectral Estimation: Theory and Applications, Prentice Hall, 1987.

[7] M.S.Rizk, et al, "Novel decision strategy for P-wave detection utilising nonlinearly synthesised ECG components and their enhanced pseudospectral resonances," IEE Proceedings Science, Measurement and Technology, Special section on Medical Signal Processing, vol. 147, No. 6, pp. 389-397, November 2000.

[8] M.S.Rizk, et al. Non-linear dynamic tools for characterising abdominal electromyographic signals before and during labour. Transaction on Instrumentation, Measurement and Control, vol. 22, pp. 243-270, 2000.

[9] J.C.Principe, D. Xu, and C. Wang, "Generalised Oja's rule for linear discriminant analysis with Fisher criterion," Proceedings of the International Conference Acoustics, Speech, & Signal Processing, pp. 3401, 3404, 1997.

[10] W.A.Zgallai, "Advanced Robust Non-Invasive Fetal Heart Detection Techniques During Active Labour Using One Pair of Transabdominal Electrodes", PhD Thesis, City University, UK, 2007.

[11] W.A.Zgallai, "The application of adaptive LMF quadratic and cubic Volterra filters to ECG signals," International Journal of Computer Theory & Engineering, Badawy, W. Ed., IACSIT Press. Vol. 7, No. 5, pp. 337-343, October 2015.

[12] W.A.Zgallai, Second- and Third-Order Statistical Characterization of Non-Linearity and Non-Gaussianity of Adult and Fetal ECG Signals and Noise, Chapter 2 in Practical Applications in Biomedical Engineering, Andrade, et al., Eds., ISBN 9789535109242,. January 9, 2013.

[13] W.A.Zgallai, Detection and Classification of Adult and Fetal ECG Using Recurrent Neural Networks, Embedded Volterra and Higher-Order Statistics, Chapter 11 in Recurrent Neural Networks and Soft Computing, ElHefnawi, Ed., InTech Open, ISBN 9799533075463. 2012.

[14] M.Rizk, et al. "Modified MUSIC Pseudospectral Analysis Reveals Common Uterus and Fetal Heart Resonances During Labour Contractions", the 22nd IEEE EMBS, EMB2000, USA, 23-28/7/2000.

[15] W.A. Zgallai, "MUSIC fetal heartbeat detection during uterine contraction," International Conference on Biomedical Engineering and Environmental Technology, London, UK, 21-22/3/2015.

AUTHORS

Dr. Walid A. Zgallai

Dr. Zgallai was born in Tripoli in 1969. He received his BEng in Electrical and Electronic Engineering from Kuwait University, Kuwait, Kuwait, 1992, BSc Degree in Electrical Engineering from Tripoli University, Tripoli, Libya in 1992. He received his MSc degree in Communications and Signal Processing from the University of London, London, UK in 1993 and a Diploma of Imperial College (DIC), London, UK in 1993. He received his PhD degree in Electrical Engineering from City University London, London, UK in 2007. He also obtained a Postgraduate Certificate in Learning and Teaching from the University of West London, London, UK in 2009.

He worked as a Teaching Assistant, Research Assistant, Research Associated, and Postdoctoral Research Fellow at City University London, London, UK from 1998. He worked as a Senior Lecturer and Programme Leader at the University of West London from 2008. He works as a Faculty and Programme Leader of Biomedical Engineering at the Faculty of Engineering Technology and Science at the Higher Colleges of Technology, Dubai, UAE. He authored 30 publications published in international peer-reviewed journals and conferences. Research interests include detection and classification of ECG signals including abnormalities as well as transabdominal fetal ECG signal during labour, adaptive filtering, non-linear and non-Gaussian signals in non-stationary environment, neural networks, higher-order statistics, and chaos and fractal signals.

Dr. Zgallai is a Fellow of the Higher Education Academy in the UK, FHEA. He is a member of the IET, member of the IEEE, and an Associate Member of the Institute of Knowledge Transfer in the UK. He serves in many academic committees, including accreditations, he has been an external examiner at international HE institutions.