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Portable Real Time ECG Monitoring

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Annotation: The use of computers in biomedicine has made a revolution in this field since it greatly facilitated diagnostic procedures, as well as the analysis of the obtained results. Electrocardiography is certainly one of the pioneers of this field. Starting with bulky and heavy devices for registering heart activity, today it has come to the point that for some basic identification of the heart rhythm, it is enough to have a small and cheap sensor plate. Of course, the question of the accuracy of such sensors remains, but they can be used for research, education, and even initial diagnostics. One of such sensors is also presented in this paper. How the sensor is integrated into a system that can successfully register the human heart is also described. Authors of and used ECG sensor as wireless wearable device to be used in portable form. In, the authors showed the potential of medical-grade ECG sensor in medicine, sports, veterinary, etc.

Overview

This thesis explored the expertise of clinicians as they interpreted ECGs from the perspective of diagnostic accuracy. This was achieved by analysing the eye-movements of the clinicians in order to determine if there were any links between eye-movement behaviour and interpretation accuracy. Understanding how people make correct ECG interpretations is important, as inaccurate interpretations lead to poor, or inappropriate patient care [Mele, 2008]. Improving ECG interpretation remains of the utmost importance, as both human experts and automated/computerised methods still make frequent interpretation errors [Macfarlane et al., 2017]. Human experts may not be aware of their limitations [Bond et al., 2014], and may disagree with each other [Salerno et al., 2003a]. Conversely, automated methods are still not clinically reliable enough for subsequent decision making to occur without the overview of an expert human interpreter [Schl¨apfer and Wellens, 2017]. This work is important because it makes contributions to our understanding of the differences between people that make correct interpretations and those that do not. This has a potential benefit in terms of providing foundational information for designing training programs and resources, as well as toward potentially better algorithm designs for automated approaches. Differences between expert and novice practitioners, and the attributes that give experts superior diagnostic abilities compared to novices is an interesting topic but it does not tell the whole story. This thesis is the first to focus not on particular groups per se, but instead the accuracy of individual clinicians. Arguably, although more challenging to analyse, accuracy is of higher clinical importance. None of the experts in any of the experiments carried out in this thesis, or any other ECG based eye-tracking study have achieved 100% accuracy [Bond et al., 2014, Wood et al., 2014]. This means that expert or not, errors in interpretation occur frequently. Examining what, if any differences that may exist in visual behaviour as a function of accuracy provides a richer understanding of this complex medical skill.

Much of the early work examining visual behaviour during ECG interpretation is qualitative and/or uses simple eye-tracking metrics to examine proxies of attention [Holmqvist et al., 2011]. Where differences in groups are explored, they are always focused on comparing expert and novice groups. No work to date has examined this from the perspective of accuracy of interpretation. In addition to this, no deeper quantitative exploration of ECG interpretation has been attempted. This work aimed to answer the following questions:

- Is there a quantifiable difference between the visual behaviour of people who interpret an ECG accurately, and those who interpret it inaccurately?
- Is it better to group eye movement data for analysis at the level of the lead, or using a finer level of granularity?
- What effect does the presence or absence of an associated patient history have on accuracy of ECG interpretation and visual behaviour?
- How does experience affect ECG interpretation? How does the interpretation of the ECG change in the presence of increased experience and what is the nature of these changes (if any?)

To answer these questions, a substantial analysis of an existing data set and a further study were carried out to capture data from the eye-movements of practitioners that interpret ECGs as part of their usual clinical role, or their training (if they were a student). This was also supported by the collection of qualitative data, in the form of interviews and questionnaires, that were used to substantiate findings, and provide a deeper understanding of the underlying processes involved in ECG interpretation. Following the initial examination of the data using the standard eye-tracking metrics, the eye-tracking data were also visualised to aid understanding and provide additional.

hypotheses [Blascheck et al., 2014]. This led to the focus on the STEMI (heart attack) stimulus, due to its clinical importance and the ground truth available in the teaching texts, concerning where practitioners need to focus attention in order to identify the salient features that would lead to a correct subsequent interpretation [Jenkins and Gerred, 2005, Wagner, 2008, Davies and Scott, 2015]. Following differences seen in the scanpaths with the visualisations, and statistically with the Levenshtein distance, a greater focus was placed on transitions between leads from the perspective of the cross referencing of salient features. This then led to the development of a quantitative technique to examine transitions between the ECG leads. Following on from this, the level of data grouping was considered, as examining lead based transitions may not have been revealing the true picture, as it does not consider cross referencing and checking of the waveform within the leads. To overcome the biases inherent in such processes, a data-driven grid based solution was designed and tested in an additional study examining artwork, where a description of the painting was used in lieu of associated clinical data. Finally this technique was applied to a new set of ECGs that focused on the STEMI conditions and utilised clinical history. The two approaches to data grouping, lead based and grid based were then contrasted.

1. Main findings and implications

The initial step for investigating the phenomenon of ECG interpretation from a visual perspective was to examine what practitioners themselves knew about how they carried out the process. To this end a set of interviews were analysed for prevalent themes that might give some clues about the underlying process. The thematic analysis led to the formation of a perceptual model of ECG interpretation, based on expertise. A duel-process system was identified, with more experienced practitioners able to apply a pattern recognition system, compared to a slower and more systematic approach applied by the less experienced. It was also highlighted that experts could revert to the slower system when encountering barriers to interpretation. Although previous work highlighted that pattern recognition was used by experts, with novices using stricter protocols [Bond et al., 2012, Bond et al., 2014], these studies did not consider the relationship between these features and other factors, such as knowledge of the patient, and barriers to interpretation. These richer details were identified through the thematic analysis as having an influence on the underlying process. Although some authors state that methods for ECG training should be carried out in less time pressured environments than busy clinical departments [Hoyle et al., 2007], it may actually be beneficial to sensitise practitioners to these environments early on in their training. As clinical environments, and hospitals in particular are known to be busy and full of distractions [Davies et al., 2016], repeat exposure to interpreting in these environments may help to reduce the barriers associated with pressure and stress, especially as repeat exposure to a stressful stimulus has been shown to reduce anxiety [Abramowitz et al., 2011]. As many participants identified in the survey (Chapter 9) that they were trained on the job by colleagues, these changes would be potentially easy to introduce.

Following the insights given by practitioners from the interviews, the eye-movement data were then analysed looking at interpretation accuracy. The average accuracy for the participants was 48%, which seems very low for practising clinical professionals. However we must consider that the accuracy stratification was quite strict, requiring diagnostic level accuracy. There was also quite a spread of conditions represented in the presented ECGs, some of which were challenging cases. We see that with the second study that focused more on the STEMI ECGs that accuracy rose to 64%. This still seems low, but when we consider that in a previous study experts with an average of 30 years' experience only scored 63% [Bond et al., 2014], we see the inherent complexity posed by ECG interpretation and why efforts to improve diagnostic accuracy are so important for subsequent patient care [Wong, 2017].

It was also found that there was no strong correlation between experience and accuracy. This links back to what was discussed by some participants in the interviews, where they described that promotion and diversification of the diagnostic procedures they were involved in reduced the time and frequency they spent interpreting ECGs, leading to forgetting skills over time. This clearly had an impact on their subsequent accuracy, highlighting the importance of continual practice to maintain skills, especially as these skills have been shown to decline rapidly over time [Raupach et al., 2016], and it is recommended that competence should be maintained and displayed by periodic reviews [Eldridge et al., 2017]. This also demonstrates the value of the approach taken in this thesis; analysing behaviour as a function of accuracy, rather than naively assuming that expert and novice groups will capture meaningful differences. Another finding was that people fixated the least on the historically neglected lead aVR [Tamura, 2014], despite its diagnostic importance [George et al., 2010]. This was confirmed by the survey (Chapter 9), in which practitioners self identified that they paid the least attention to this lead. This was also the case in the exploratory study carried out by Bond et al. [2012], using a single clinical scientist that viewed lead aVR for only 1% of the total viewing time [Bond et al., 2012]. This was not however the case for the larger expert study [Bond et al., 2014]. The implications of this again suggest that training programs should highlight the diagnostic value of this lead to ensure that it is not overlooked, which could lead to missing potentially important clues to the presence of various pathologies [George et al., 2010].

The next stage involved the visualisation of eye-tracking data in order to generate hypotheses. This was done because visualisations can aid in data discovery [Field et al., 2012]. Analysis of eye-tracking data thorough visualisation has been shown to aid in the understanding of relationships within data, as well as assist in the exploration of spatio-temporal features of eye-tracking data [Blascheck et al., 2014, Kurzhals et al., 2015]. In their survey of the use of visualisation for eye-tracking data, Blascheck et al. [2014] highlight the increasing importance of visualisation in eye-tracking data analysis. They rank visualisation techniques by features, such as temporal/spatial and whether it is for single or multiple users. This is further subdivided into AOI based, point based or both and classified by stimulus type, and whether it is static or dynamic, 2D or 3D. Based on these classifications, the matching dotplot sequences, analysed with linear regressions and subsequently clustered, were identified as the most relevant to the ECG stimuli, as they were AOI based, spatial and for static 2D images [Goldberg and Helfman, 2010].

Although many more visualisations have been created in recent years, they are often for more complex dynamic stimuli, such as videos. The dotplot clustering technique described by Goldberg et al. [2010] was not implemented due to certain issues, such as forcing each scanpath to be in a single cluster, when in fact they could exist in many. A lot of eye-tracking visualisation techniques are complex, take time to implement and can be difficult to interpret. Using the simpler approach of visualising the scanpath similarity using the Levenshtein distance allowed for rapid comparison of all participants or subgroups in a measurable quantitative way, without increasing visual complexity. These visualisations led to the findings that in some stimuli, the scanpaths were much more similar than in others. This also allowed us to see the idiosyncratic nature of eye-movements and spot extreme outliers at a glance. The use of the nearest neighbour index highlighted that fixations were spatially clustered, allowing a quantification of this phenomenon. The heatmaps also showed the clustering of attention around certain salient features of the ECGs. The index also established a measure, showing that the least relatively clustered stimuli (hyperkalaemia) was also the one that the most participants failed to interpret correctly. As the visual search was less relatively clustered for this condition, it could indicate that the bottom-up salience generated by the stimulus is beginning to reduce, as the interpreters begin focusing elsewhere for more subtle clues. The implications of this are that it may be possible to quantify the point at which the bottom-up salience begins to loose its attentional dominance. This may be the time when top-down knowledge begins to override the process and influences greater control of the visual search. Scanpath analysis presented a deeper and richer picture of behavioural activity than eye-tracking metrics, such as fixation duration and count. Visualisation and distance measures that overcame some of the limitations presented by standard inferential statistical approaches were employed to deal with very different group sizes and non-normal distribution of data. Following the insights gained into scanpath differences, the STEMI was examined in greater detail. The STEMI represents a time critical emergency, where stratification of treatment options, such as fibrinolysis or primary PCI1 are dependent on prompt and accurate ECG interpretation [Wong, 2017]. Many ECG courses and training texts (i.e. [Jenkins and Gerred, 2005, Bowbrick and Borg, 2006, Wagner et al., 2013, Davies and Scott, 2015]) all discuss the importance of cross referencing ST-elevation in multiple ECG leads, in order to interpret a STEMI, and differentiate it from other conditions that also present with ST-segment elevation. This ground truth led to the hypothesis that more transitions would likely occur 1Percutaneous Coronary Intervention between the leads exhibiting signs of ST-segment elevation, in the group making a correct interpretation. The n-gram analysis carried out seemed to indicate that on average, shorter bigram sequences were more prevalent than longer sequences. The bi-gram based transition matrices reflected descriptive differences in the transition frequencies between the two groups. In order to determine if these differences were significant and quantify them, accounting for the variation in group sizes, a probabilistic method was applied [Davies et al., 2016]. This method compared the difference between transition matrices represented as Markov chains, and used permutation tests to generate a comparable distribution from the available data. The results did show transitional differences for 3 stimuli between the accuracy groups. Whether these differences were driven by the type of stimuli, or some top-down factor, such as different professional training was not clear. It did however provide supporting evidence that differences in transition behaviour were detectable, and may be of importance for some conditions more than others. As permutation tests are known to be robust against type I error [Wilcox, 2010], this suggests that widespread differences do exist in the transitions, just not at the standard alpha of 0.05. There is much debate about the arbitrary traditional application of these alpha values in empirical research [Field et al., 2012].

In light of the fact that we are looking for any signs of difference that may be worthy of future research, the results from these tests do indicate that some effect is present, and that it is worthy of future consideration and investigation. Following these findings, thought was given to the grouping of data for the transitional analysis. In the first analysis this had been achieved by mapping AOIs onto each ECG lead. This is a reasonable starting point as the lead offers a semantic self-contained region with a specific data signal presented in each lead.

We know however from the plethora of ECG training texts that rather than just the lead, the specific components of the waveform require identification and assessment against a 'normal' morphology. One approach would have been to map an AOI onto each of the waveform components. This would have been impractical for many reasons: chiefly, it would be extremely time consuming and prone to human error, additionally the different sized AOIs would have made direct comparison more challenging. To overcome errors inherent with eye-tracking accuracy, the AOIs also would need to be above a certain size, between 1-1.5◦ [Holmqvist et al., 2011]. A data-driven approach was applied, using a clustering algorithm (DBSCAN) to derive the cell size for the areas. This supports the creation of equally sized units of interest that are amenable to analysis, and derived from the gaze behaviour of the participants. To establish the practicality of this approach, and to avoid over-fitting, the technique was applied to paintings, as they have highly subjective semantic areas, and/or differing sizes. A grouping factor was introduced in terms of painting narrative, that was intended for substitution with clinical data, when applied to the ECG problem. The results of this study found that it was practically possible, and it would even work in conjunction with a relatively high number of permutations (10,000). The experiment highlighted that we obtained different information about behaviour by combining a standard inferential statistical investigation with these transitional analysis techniques, to derive a richer understanding of the underlying phenomenon. According to Orquin, Ashby and Clarke [2016], the size of an AOI appears to have little impact on subsequent results, with the exception that AOIs that were larger than an eye-trackers' absolute hardware accuracy did account for an increase in predictive power [Orquin et al., 2016]. The grid applied in this thesis was larger than the minimum size required by the eye-tracker, and did detect a greater difference. This suggests the difference could have been driven by the stimulus, with the level of the waveform within the leads being more predictive of behavioural changes than the leads as a whole. The implications for the use of the grid method are a bias reducing, data-driven method that can segment a stimulus space, and examine transitional behaviour. Additionally the technique can be used to generate data-driven, quantitative heatmaps that are easy to compare statistically. The technique may also be of use when examining phenomena that would benefit from more complete signal detection [Orquin et al., 2016]. The final stage was to take what was learnt through the previous experiments and apply it in a final investigation. The final study aimed to address the impact of clinical information in the form of a brief history of the presenting complaint on accuracy, as well as overcome some of the limitations in the initial study, such as the varied layout types and the wide spread of conditions presented. The presence of history was mentioned by several participants in the thematic analysis as an important factor in interpretation accuracy. Additionally previous work found that a brief clinical historydid have a positive influence on interpretation accuracy [Hatala et al., 1999]. Noncardiologists were also found to be influenced more by clinical history and additional information, such as automated computer interpretations [Salerno et al., 2003c]. The effect of history on ECG interpretation was more recently cast into doubt, where no statistically significant effect on accuracy was found [Wood et al., 2014]. As such, greater clarification was sought relating to its potential effect. The STEMI stimulus was also chosen to be the main ECG of interest, owing to its clinical importance, and ground truth regarding the need to cross reference leads. Other conditions were used as distractors, so participants would not become aware that the majority of stimuli were STEMI's. Taking this as a starting point, the top-down lead mapped AOIs and the bottom-up grid based AOIs were both used to examine the visual transitions at different levels of granularity. Finally we gathered qualitative data, via a post task survey, to help provide a richer understanding of the process. Findings from the experiment showed that patient history, at least in this form, did not appear to influence interpretation accuracy, supporting the findings of Wood et al. [2014]. The grid AOIs were able to detect differences that the lead analysis did not. This suggests that for the analysis of how people interpret the ECG, the lead is too coarse a level of granularity to detect the complex visual behaviours taking place within the leads, as practitioners examine the different waveform components. 2012]. The implications for this, in line with clinical training, suggest that analysis needs to take place within the leads, not just between them. Another finding was the admission that practitioners did not always check the calibration settings of the ECG, despite the fact that this is a known cause of interpretation error [Davies, 2007a]. This suggests that the importance of the interpreter checking the recording settings should be reiterated during training, especially as the person interpreting the ECG is not always the same person that recorded it [Davies, 2007a]. It appears that to truly understand the complex phenomenon of ECG interpretation from the perspective of accuracy using eye-tracking, multiple analysis techniques need to be applied and combined. Findings from inferential statistical approaches only go so far, and are not always applicable in this situation. When combined with other techniques, such as scanpath comparisons and transitional analysis, a more complex and richer understanding of the data is presented. This likely reflects the different levels of trainingexperience and medical role, as well as the underlying ECG, and the practitioners' familiarity with it. Nevertheless, differences in eye-movements were detected and hold promise for further understanding, supporting the theory that cognitive processing occurs for the part of the visual stimulus that is being visualised at that point in time [Kurzhals et al., 2015].

Limitations

Although the results of the lab-based studies may not be directly generalisable, they do make advances in behavioural analysis in this important medical field, and more widely. The results reveal the complex nature of ECG interpretation and indicate that there is still much work to be done in this field. There was a limitation concerning ecological validity. Although efforts were made to improve this by allowing participants as much time as required to interpret the ECG, the ECGs displayed on a computer screen do not mirror the way interpretation takes place in a busy hospital ward, with other distractions and access to the patients themselves.

The level and type of history used is also of question. Although efforts were made to provide this clinical information in a style similar to other studies and training texts ([Hampton, 2003, Wood et al., 2014]), the relationship between the underlying condition and the history can be of more or less importance, especially for different professional groups. For example cardiac physiologists, and some nurses often report on the ECG in terms of its criteria, and do not attempt to make a diagnosis, doctors on the other hand will make a diagnosis and therefore the history may be a greater factor for this group. It would have been interesting to examine differences in interpretation accuracy between different professional groups.

Recruitment of participants in this area is difficult and time consuming, as these professionals are extremely busy, and often difficult to access. This made the creation of comparative professional groups impossible for this particular PhD study. The current limitations of eye-tracking hardware prevent suitably sized AOIs being generated for the waveform components of the 12-lead ECG, without enlarging the ECG to such a point that it would reduce external validity by making it unrepresentative of a real ECG seen in clinical practice.

Future research

Higher order Markov chains could be used to represent more complex transitions, although coupled with a grid and permutation tests, limitations of computer hardware may make such an endeavour impossible, or extremely time consuming. Varying the type and detail of the patient history used would also be an interesting avenue for further work, as would the analysis of how different professional bodies perform in terms of accuracy and eye-movement behaviours. It is possible that due to different training and professional considerations, doctors, nurses, paramedics and other professionals have very different approaches to the task. These potential differences would also be worthy of exploration.

Another action that could be implemented to improve ecological validity would be to use eye-tracking glasses to capture data from clinicians interpreting ECGs in their natural clinical settings. Although it should be noted that without the screen as a frame of reference, analysis of the eye tracking data would become vastly more complex.

The application of the findings of this thesis could be used in several different areas. One such important avenue would be to provide real-time perceptual feedback for practitioners as they interpret ECGs, by showing them their own eye-movements. Previous work that applied this to X-ray images found that radiologists often fixated on the relevant areas, without necessarily knowing the significance of what they were looking at. When perceptual feedback was introduced by showing them their fixations, a 20% improvement was detected for the radiologists as they scanned for chest tumours [Krupinski et al., 2013]. If the same phenomenon exists for ECG interpretation, it could be used in training and clinical assessment to boost performance accuracy. Another application could be using the knowledge gained from human behaviour to work along side other automated methods, such as machine learning techniques, to enhance accuracy by combining the analysis that machines do best, such as precise measurements of the waveform components, with those of human experts, such as their ability to cope better with noise and missing data, as well as their discriminant attention on various salient features. Ongoing issues in automated interpretation include the combination of sensor data and clinical history, as well as more reliable estimations (i.e. QT interval, P wave identification to name a few) [Clifford et al., 2006]. Until these limitations can be overcome and reach clinical accuracy, humans will still be required to make the final interpretation and subsequent patient treatment plan.

Recommendations

From these findings several recommendations for clinical practice and training can be made, including;

- Training programs should highlight the diagnostic importance of lead aVR
- They should also state the importance of checking the calibration settings prior to making an interpretation
- The continual updating of skills should be promoted, especially if practitioners no longer perform this task routinely
- Training should aim to mitigate the barriers to interpretation where possible. This can be done with regular skills updates, reducing noise on ECG recordings and trying to reduce any stress or panic associated with interpretation. Possibly, by either allowing clinicians adequate time to make an interpretation, or training them to interpret ECGs in busy time demanding environments, by introducing them to the environment early, with adequate supervision.

Conclusion

This thesis has made contributions to the fields of eye-tracking and medical science. For the analysis of visual behaviour during complex task performance, new methods of transitional analysis and stimulus segregation have been proposed [Davies et al., 2016, Davies et al., 2018]. This has led to a greater understanding of how people interpret ECGs from a medical perspective, casting light on the level of analysis that is best for examining ECG interpretation with eye-tracking data.

The type of history, and the connection to underlying pathology however, may interact at a more complex level that cannot be identified by simply including history, or not. Detectable and measurable differences were found between those making correct and incorrect interpretations, suggesting that eye-tracking is a valid method fo applying the 'mind-eye' theory (what you look at is what you think about) to ECG interpretation. To truly explore and try to gain a greater insight, the combination of inferential statistics and transitional/scanpath analysis should be used in tandem for a richer and deeper analysis than each provides alone. The qualitative data collected also provides context and a deeper level of understanding of the processes involved in ECG interpretation. It appears that the underlying stimulus drives attention to a greater extent than top-down knowledge does. In most cases attention is similarly distributed across both accuracy groups. The primary difference seems to be how these features are subsequently perceived, with the correct group applying an understanding of how the salient features are linked to the underlying pathology. There is also a potential to feedback some of these findings into automated interpretation algorithms. Bond et al. [2014] states that, ambitiously findings from eye-tracking about how people interpret ECGs could be used to enhance these approaches.

A deeper understanding of the differences between practitioners who make accurate interpretations and those who do not can help to improve aspects of ECG interpretation, and ultimately enable more reliable clinical decisions to be made. This study also has potential implications for both future training and decision making regarding ECG interpretation. Finally the eye-tracking techniques described in this thesis can be applied to other areas of task performance, that work over complex stimuli, and that are able to deal post hoc with differently sized groups.

Conclusion and Future Work

The work described in this thesis has been concerned with the development of a motion artefact denoising algorithm and classification algorithm for ECG. Two new algorithms are developed, one for removing non trivial noises in ECG and second for ECG arrhythmia classification using features extracted with ICA. A new feature set is developed which includes dynamic ECG features along with ICA extracted features.

Propose and develop the algorithm for denoising of

ECG signals using ICA

The proposed algorithm deals with uncommon noises presented in ECG data during holter and telemedicine applications. Proposed method connects well-known FastICA algorithm with a correlation factor and kurtosis in order to identify noise and reduce it. This study investigated the performance of PCA and ICA in denoising ECG signals recorded in ambulatory conditions. A simulated database formed by the combination of clean ECG signals with electrode motion artefacts scaled to different levels of energy is developed for evaluation. Sensitivity of the beat detection algorithm after filtering with ICA is 100 %, even for very noisy signal. High classification accuracy and positive predictive value of ICA filtered signal are recorded. 40 % improvement in the sensitivity of ICA filtered signal for SNR of -12 dB is achieved. An automatic method based on kurtosis and correlation coefficient for component selection is proposed. Filtering, using this method, achieved 100 % sensitivity in beat detection as compared to non-filtered signals, especially when the noise level is high. As a limitation of this study, it should be noted that some stationarity has been assumed, as signals are of 10 seconds length. The performance under shorter duration noise is not studied. Although this is acceptable during the algorithm development and performance optimization practice, it does not provide the necessary realtime performances required for continuous and remote monitoring of ECG on-the-move. Another limitation to the current study is that it has been tested on a database in which clean ECG and noise signals are artificially combined. Additional tests are needed to be done in real-time situations to understand and expand the scope of the proposed algorithm.

The proposed method performed better than referential methods in the presence of all common types of artefacts. FastICA algorithm has better performance as compared to other ICA algorithms discussed in literature. The time requirements of our algorithm are decreased due computational simplicity of the FastICA algorithm. This ability is very valuable in medical applications.

Proposed and developed the algorithm for arrhythmia classification using ICA

The algorithm is proposed for ECG arrhythmia classification by using features extracted with ICA. The classification experiments are performed on the MIT-BIH arrhythmia database. For this study, eight types of ECG samples which includes the normal sinus beat and arrhythmias, are used. Proposed method combines Independent Component Analysis (ICA), Pre-RR Interval, post-RR Interval and QRS Segment Power for feature set and neural network classifiers for ECG beat classification. A new feature set combined dynamic ECG features along with ICA extracted features. Optimal selection of the number of ICs for best classification accuracy is made. Computer simulations show that ICA based feature extraction method performs better than any other available method. Neural network classifiers demonstrated high classification accuracies of over 99.5% with a relatively small number of ICs. It also proves that selecting relevant features from the feature set could improve the recognition performance, which makes a robust feature set for ECG arrhythmia classification. Comparison of classification accuracy, specificity and sensitivity with other state of the art method is done and its efficiency is proven. The results prove that the proposed scheme is a promising model for arrhythmia detection of clinical ECG signals.

All goals formulated were successfully met. Two algorithms were proposed– one for denoising of ECG recording containing trivial noise and the second algorithm for classification of eight different types of ECG arrhythmias. Both algorithms were tested against the state-ofthe-art methods and results were decent. Both algorithms were capable of dealing with uncommon noises. This makes them very useful in applications within telemedicine issues and holter recordings, where the environment is rapidly changing and the distortions corrupting the ECG signals could be very different from those normally present in ECG within the laboratory or clinical measurement of ECG.

Future Work

Although the results presented here have demonstrated the effectiveness of the Independent Component Analysis for removal of motion artefacts and feature extraction of ECG signal and it could be further developed in a number of ways:

Extending the Algorithm for Real-Time Application

To extend the proposed batch-processing algorithm for real-time applications, computation should be done in sliding overlapping windows. There are several shortcomings in running algorithms in sliding overlapping windows, including reduced algorithmic performance, increased memory requirement and increased computational load, which needs to be resolved for a streamline implementation.

Extending the Algorithm for Other Classifiers

No classifier is perfect; the best classifier's performance is to correctly classify novel cases. Performance is related to both classifier design and testing. Occasionally complex classifiers fit 'noise' in the training data, achieving low accuracy when presented with novel cases. Our classification results showed a different accuracy of each arrhythmia with same classifier. Using multiple and hybrid classifiers can result in improving classification accuracy and stability. The future work will aim at extensive testing of our developed algorithms with real data sets in conjugation with other intelligent system classifiers.

CONCLUSION and FUTURRE sWulOtsRK

Conclusion

The key aims of this project were to investigate the effect of graphene (GN) on ECG acquisition systems and to obtain GN-based ECG electrodes for providing higher quality ECG signals when compared to those obtained by traditional Ag/AgCl methods. As a result of the unique structures and superior characteristics of GN and its derivatives, GN-based nanomaterials are amenable to be used in a wide range of applications, including biomedical and biosensor applications. Due to high electrical conductivity, free electron movement on the surface and the availability of fabrication of many GN-functionalised nanocomposites, it is favourable for the synthesising of high performance electrode materials. These superior properties of GN make it possible to achieve the desired sensitivity and measurability for several targets in bio-sensing applications. Several studies concerning ECG sensing applications applied using different types of materials were critically reviewed and the outcomes analysed. It was observed that there is a high demand for robust, reliable, sensitive and accurate ECG monitoring devices in which different types of materials can be used to fabricate new sensors for ECG applications.

In this work, a novel graphene (GN)-coated ECG electrode was developed and its performance was tested in terms of quality-of-signal and durability. The electrodes were obtained by CVD grown on Cu and the structures were transferred to Ag substrates. The experimental results clearly showed improved performance with graphene-coated electrodes. The signal-to-noise ratio has been improved significantly by 12% to 23%, due to GN coating, whilst the quality of the ECG signal in terms of the shape of its morphology is much better when compared to electrodes without GN coating. It was also found that the quality of GN-coated electrodes was not significantly degraded even after multiple uses (10 times). In sum, the experimental results revealed that the obtained ECG signals from 10 different subjects were improved using GN-coated electrodes compared to those when conventional adhesive Ag/AgCl electrodes were deployed.

The characteristics of graphene coating on the conventional electrode were also investigated experimentally using SEM images, Raman spectroscopy, and impedance measurements.

The measurements/observations from these experiments have clearly an improvement due to graphene coating. The SEM images show a smoother surface of GN coating, which would increase skin-toelectrode contact. The Raman spectroscopy measurement confirms that there is no presence of the 2D-band before the GN coating process, however, however, Raman spectrum consists of a pronounced 2D-peak of comparable intensity to the G-peak and a pronounced reduction in the full width at half maximum (FWHM) of the D- and G-bands (see Figure 4.17a and b). As mentioned earlier, these Raman spectroscopy measurements fit with single-layer GN deposition onto a substrate, thereby evidencing separation of itself from the case of graphite or multiple-layer GN deposition. Impedance measurements of the proposed ECG electrodes have shown a lower level being exhibited in GN-coated electrodes when compared those without coating, which increases the sensitivity of the electrode (65 k versus 445 k at 20 Hz).

Finite element modelling (FEM) of a skin–electrode was also developed to understand the electrical activities of such an interface model. The simulation results suggest that the GN coating improves the current density and electric field in the region of interest by a factor two when compared those obtained by Ag-coated electrodes. These results hold promise for further development of the new nanomaterial-enabled dry electrodes for electrophysiological sensing in wearable technologies.

Furthermore, electrode placement investigations were carried out with different scenarios to find out a measurable ECG signal from near the ear to develop an ear-based multi-functional wireless wearable monitoring system. Subsequently, an ear-lead multiple smart sensor system was presented in this project with a 3D printed earbud design, which integrates the ECG and CBT sensors together. First of all, an ECG electrode set-up was demonstrated as obtaining ECG signals from behind-the-ear in contrast to traditional chest-based measurements. The results acquired are very promising, whereby detection of the components of an ECG signal (P-wave, QRS complex, and Twave) is highly achievable using graphene-based electrodes. The proposed ear-based multifunctional device has a number of advantages: fixed electrode positions; user comfort; robustness; user-friendliness; and it is a reduced motion artifact as well as being discreet. Due to these advantages, an ear-based physiological monitoring system was modeled with continuous monitoring on an Android based smartphone, providing real-time data control for the patients and also clinicians. This device includes non-intrusive sensors for ECG, CBT, and PPG with high accuracy. Moreover, an Android based app was developed and tested, in order to display ECG, CBT, HR, and SpO2 physiological data on a person's smartphone. Moreover, observations were made of the influence of sensor positioning on signal quality and skin-electrode contact impedance using various types of ECG electrodes. Even though a chest-based sensor positioning provided the best SNR (27.03 dB) and lowest contact impedance values (65 kΩ at 20 Hz), an ear-based proposed sensor system also demonstrated promising results (22.96 dB SNR with GN-coated electrode) compared to other prototypes. Additionally, the proposed system ameliorates the difficulties of wearable devices, giving patients significantly less restriction by eliminating the need for adapting intrusive equipment or using a laptop to monitor the obtained physiological data. The design of the proposed ear-based multiple smart sensor system also provides wireless transfer of data usingBluetooth technology to connect to a smartphone for further analysis. Experimental results and analysis clearly exhibited the feasibility of the concept and interoperability of the biosensors as well as providing solutions to key technological and scientific problems.

Future Works

First of all, the proposed GN based ECG sensor still has PMMA residues left from transferring graphene grown by chemical vapour deposition (CVD), which remains a challenge for maximising the effect of GN in regard to ECG monitoring. New approaches can be developed for a simple cleaning method for removing PMMA residues that can reduce impairments to the electronic properties of GN-coated electrodes. If a high-quality graphene coating process on Ag substrates can be carried out, then skin-electrode impedance can be much reduced and the proposed ECG sensor's performance can be improved further.

Furthermore, the developed mobile healthcare platform could be extended by applying the following suggestions in order to minimise the data acquisition module and to achieve even more promising performance regarding physiological signals monitoring.

- In this study, adhesive gel was applied to GN-coated electrodes for acquiring ECG signals from the body. Implementation of GN based dry type ECG sensors could help in conforming to the skin without the need for adhesive gels, thereby improving the impedance of the skin-electrode interface. To this end, another dry type ECG electrode could be fabricated with GN coating using the CVD process in the future. Likewise, other GNproduction techniques can be utilised to synthesise dry type ECG electrodes, such as liquidbased exfoliation and further comparisons could then be made
- In this research, GN has demonstrated valuable electrical characteristics when coated with Ag substrate in ECG monitoring, as exhibited in experimental results. Apart from ECG acquisition, GN also can be grown on sensors for temperature and SpO2 measurements. Fabricating GN-based temperature sensors and photodetectors can result in better performance for CBT and PPG monitoring due to sensitive temperature coefficient resistivity and rapid responsivity characteristics.

- Implementing a PPG sensor on the ear lobe can minimise the multifunctional experimental development and the proposed system will be capable of integrating with other ECG and CBT sensors in an ear-based device.
- The designed system may be developed further within printed wearable electronics to enhance the level of comfort, flexibility and wearability of multiple physiological sensors, which can be combined into a single, unobtrusive and ease-of-use miniaturised package.
- Fabrication of a flexible and wearable hybrid electronics patch means that it can be worn near the ear area, whereby the motion of the artefact can be minimised with a discreet solution. The signals detected from these sensors can then be wirelessly transmitted to a smartphone, in which a dedicated app will be installed for continuous monitoring and obtaining further physiological measurements, such as blood pressure and heart rate variability (HRV).

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