ECG monitoring techniques using advanced signal recovery and arm worn sensors.

William D. Lynn
School of Engineering, University of Ulster
Shore Road, Newtownabbey, UK
lynn-wd@email.ulster.ac.uk

Omar J. Escalona
Engineering Research Institute, University of Ulster
Shore Road, Newtownabbey, UK
oj.escalona@ulster.ac.uk

David J. McEneaney
Cardiac unit, SHSCT
Craigavon Area hospital, Portadown, UK
David.McEneaney@southerntrust.hscni.net

***Abstract*—Techniques for monitoring ambulatory patients have advanced greatly over the past 10 years. The advent of pocket computing, in the form of cellular phone technology, being one of the prime drivers. Until recently there was a great functional deficit in the performance of the average portable microprocessor and that which was used in the personal desktop computer. Today, smart phones have 1GHz processors and use multicore configurations. Memory has accelerated at a similar rate, with 128Gb flash memory being common place.**

The following paper discusses the viability of an arm worn 'smart' device for monitoring cardiac dysrhythmia and or electrocardiographic dysmorphia. As there is particular interest from the medical community in the field of monitoring of paroxysmal atrial fibrillation; the proposed technology will be a front line diagnostic tool for primary care clinicians, allowing them to offer a non-surgical, long term monitor. Alternatively, the commercial possibilities of marketing a clinical quality, 'smart band' cardiac monitor into the consumer space are immense.

This paper deals with emerging digital signal processing techniques as well as discussing the underlying hardware requirements that may allow the full realisation of this new technology.

***Keywords*—ECG; dysrhythmia; DSP; long term monitor; dry electrode; long QT**

I. INTRODUCTION

Heart disease remains a common killer of both the old and the young [1], making a strong case for the development of a long term monitoring technology that is non-invasive and comfortable to wear. Also, with recent research alluding toward an increased detectability of latent cardiac abnormalities as the subject stands from a seated position [2], the desirability and marketability of an arm worn smart sensor is increasingly realised [3].

The effect of drugs on the heart rhythm is widely noted in the literature. An example being those which are linked with QT elongation or torsade de pointes. Domperidone, for instance, has been associated with a small increased risk of serious ventricular dysrhythmia or sudden cardiac death [4,5]. A QT prolongation warning strategy for patients continuously monitored during their course of treatment would significantly de-risk the administration period.

Atrial fibrillation (AF) affects almost 800,000 people in the UK, predominantly over 75 year olds with an affect rate of 10%. AF is uncommon in younger people; however, it may be coincidental with other heart defects such as heart valve problems [6]. Gauging the time a patient spends in paroxysmal atrial fibrillation will determine the treatment plan. Current non-invasive analysis and recording equipment, such as the Omron HCG801 [7], does not give a good temporal picture because the recording is (a) not continuous and (b) patient intervention dependant.

The current alternative approach for long term rhythm monitoring is the implantable loop recorder. During a surgical procedure, the device is placed under the skin on the chest wall, near the heart. The recorder can monitor rhythm for two years or longer. However the recording is not continuous. A native warning algorithm monitors cardiac electrical activity within a sliding time frame. If the algorithm identifies a predetermined dysrhythmia a snapshot is taken and stored. The time frame is limited by a trade-off between time spent recording and battery life. A surgically implanted device is expensive ($2000) and comes with the risk associated with a surgical procedure – infection, anaesthetic reaction and scar formation. Therefore it must function for an extended period to justify the risk to the patient, the cost of the device, the surgery, post operative hospitalisation and subsequent follow up.

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II. Clinical Investigation

a. Methodology

The success of the proposed technology depends on the viability of signals recorded on sites such as the wrist, forearm and upper arm. These are known as distal recording sites. Each site was investigated for signal level using the industry standard recovery technique of signal averaging (SA). The technique is described fully by Escalona et al[8] and is a widely accepted method of small potential recovery.

The study maps the signal degradation as the measurement site is moved, away from the heart, along the left arm. Ethical approval for the investigation was obtained from the Office of Research Ethical Committees Northern Ireland (ORECNI). An information leaflet was provided to each subject and informed, signed consent obtained prior to participation.

Subjects were selected from the general intake of the Craigavon Area Hospital (CAH) cardiology department and recordings were carried out on different days, using the same room and equipment setup. This was a protocol decision made in order to minimise the effects of localised, intermittent radiated noise.

A database of 38 recordings of distal sites along the left arm was created. Each recording duration was 500 seconds at a sample rate of 2048Hz and 24bit resolution. The bit resolution was calculated to be 31.25e-9V. In total 12 channels plus a reference and a driven right leg (DRL) were displaced along the left arm.

b. Clinical data processing

Each recording was signal average processed using a fiducial point obtained from channel 1(CH1) – chest lead 1. The strong signal for CH1 allows for the distal channels to be temporally aligned and averaged consistently. A consistent beat recovery of 98% or greater was achieved giving an average beat participation of 348 to 512, dependant of the subjects heart rate.

A comparative noise measurement was achieved using a 120mS window centred on a fiducial point and a 40mS window displaced along the S-T segment. Temporal dispersion was used to generate a signal to noise ratio (SNR) for each subject. The results of the six best recordings are displayed in table 1. The distance from the heart progressively increases from left to right across the table, with CH6-2 being on the left wrist.

Table 1 - Six best case recordings: SNR mean values along four distancing bipolar leads along the left arm, to the wrist.

Subject	CH1	CH12-11	CH10	CH4	CH6-2
1	20.97	1.27	1.08	2.23	0.48
2	13.75	4.93	4.67	10.48	1.81
3	55.29	36.86	15.67	2.00	1.85
10	60.59	197.05	22.22	21.23	2.15
17	37.68	1.49	0.25	0.67	0.16
36	98.85	3.67	1.01	0.44	4.99
Mean	**47.85**	**40.88**	**7.48**	**6.12**	**1.91**

c. Study conclusion

The pilot study set out to investigate the signal strengths along the left arm and, in particular, the comfort zones described by Gemperle et al[9]. The mapped surface potentials provide quantitative evidence of the signal levels distributed along the arm. A SNR of greater than 1 demonstrates recovered QRS activity. The study derives the broad conclusion that 88% of the 32 recordings deemed acceptable from the total 37 group, had a SNR greater than 1 when using the bicep bipolar channel CH12-11.

III. Realtime Signal Processing

The proposed technology will require a real time noise reduction algorithm to allow accurate detection of anomalies. The latency involved when using signal averaging is extensive – 500 seconds.

a. Empirical Mode Decomposition

Empirical mode decomposition (EMD) is described extensively in the literature [10]. Firstly a comparison of SA data from Table 1 with an EMD filter was carried out. The original data used to generate the SA was truncated to a signal length of 10 seconds prior to EMD filtering. A further, small study based on an application specific protocol was also carried out. A dry electrode technology [11] was used to obtain subject data from 2 subjects.

The data of Table 2 uses the same temporal displacement noise comparison technique as that of Table 1.

Table 2 - SNR of signal averaged electrocardiogram (SAECG) compared to empirical mode decomposition (EMD).

Subject	1			2			3			
	sig	**noise**	**snr**	**sig**	**noise**	**snr**	**sig**	**noise**	**snr**	
SAECG	2.65	2.09	1.27	4.54	0.92	4.93	7.93	0.22	36.86	
EMD	0.936	0.064	14.608	163.448	25.811	6.333	188.908	6.091	31.015	
Subject	**10**			**17**			**36**			
	sig	**noise**	**snr**	**sig**	**noise**	**snr**	**sig**	**noise**	**snr**	**Mean**
SAECG	2.65	0.02	1.27	6.44	4.31	1.49	4.57	1.25	3.67	8.2483
EMD	284.105	46.026	6.173	381.860	212.238	1.799	334.054	14.230	23.474	13.9

Figure 1 shows that a definite improvement in SNR is observed when a basic EMD partial recomposition technique is used [12].

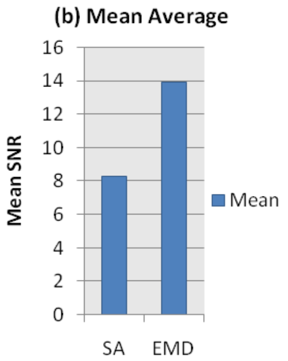

Figure 1 – Mean average SNR comparison for six cases

Table 3 presents the data from a small study, $n = 2$. In this instance the aim was to test the feasibility of dry electrode use. Each recording utilises a charge amplifier recorder and a bipolar electrode pair. The electrodes were placed diametrically across the bicep, vectored away from the heart. The position was identified, via the primary study, to be the best case of the peripheral comfort positions identified by Gemperle. Initially subjects were recorded in a typical clinical environment, this is referred to as a "normal environment". The second stage of the study required that the subjects be rerecorded in a noiseless environment. A shielded anechoic chamber was used for this activity. Gross patient motion was discouraged for this study so as to ascertain a baseline of functionality; however, small movements of the left hand were performed to create low level electromyographic (EMG) signals.

Table 3 –Dry electrode comparison between a normal environment (N) and an anechoic chamber (C). Mean value for $n = 2$.

Subject	1(N)			1(C)				
	sig	noise	snr	sig	noise	snr		
EMD	503.278	18.5992	27.06	0.035	0.0001	296		
Subject	2(N)			2(C)				
	sig	noise	snr	sig	noise	snr	Mean(N)	Mean(C)
EMD	0.0124	0.00018	68.89	0.0182	0.0001	185.8	47.97	240.906

In each case the data was filtered using the same EMD partial reconstruction algorithm used during the comparative study. The data shows a considerable, 500% increase in the capability of detection when using a shielded room. Obviously this technique is impractical, it shows, however, that the dry electrode technology is still very much in its infancy. Charge amplification utilises an extremely high impedence input amplifier which is susceptible to both radiated and coupled noise.

The EMD empirical filtering technique succeeded in extracting rhythm information for both subjects. It did so with less than 10 seconds of latency. This figure is extremely conservative as the majority of the available information can be extracted from just one ventricular complex, meaning the latency is approximately 1 second. It is notable that the EMD filtering process was not completely automated during this study. Decomposition of the input signal is dependent on its spectral components. Different signals will decompose in to varying numbers of intrinsic mode functions (IMF's). On average, the signals used during both of the studies mentioned, decomposed into 12 IMF's. However the decomposition was distributed between 7 and 15 IMF's, again dependant on the frequency components of the input signal. More work is required to fully utilise the benefits of the EMD process and allow an automated filtering algorithm to be produced.

It was also noted that mode mixing [13] was evident in the processed data of several subjects. This phenomena leads to a desensitisation of the filtering technique, as the IMF's become no longer monotonic. This may prove to be a fundamental, confounding issue with using EMD in its basic state. Further work utilising the Ensemble EMD (EEMD) technique [14] may prove to overcome the short fall in the suitability of EMD for this application. EEMD overcomes the mode mixing issue by mixing white noise with the residual component prior to the next phase of decomposition. This effectively increases the frequency of the splinic envelope, eliminating the aliasing effect which caused mode mixing.

IV. Hardware Considerations

A robust recovery method is required to support the signal processing. Failure to recover the desired signal is irreversible and no amount of post processing will facilitate extraction.

Clinical ECG equipment is described as a single-ended recovery system, ie each electrode is referenced to a common point electrode, referred to as the CMS electrode. Ideally the CMS electrode is placed a reasonable distance from the measurement electrode. A single lead ECG demonstrates this principle by placing 2 electrodes at opposite sides of the chest in order to achieve the maximum available signal. A general clinical ECG recording, due to the nature of the system, will be subject to common mode offset from electrode potential and environmental noise. However, the magnitude of the recorded signals greatly overrides the system noise, meaning that it can be ignored. A distal site ECG recorder will not benefit from a greatly displaced common point electrode. In order for the proposed device to meet the requirements of comfort and practicality, all measurement electrodes must be contained within a small area on the upper arm or wrist.

A differential measurement system will provide a solution to the majority of the noise sources encountered during monitoring. Common mode signals and coupled environmental noise will cancel leaving a clean signal representative of the bioelectrical activity. Many texts describe the use of differential biopotential amplifiers. Nagel, J. H. [15] and Webster, J. G. [16] discuss the basic requirements of a biopotential amplifier and suggest that the minimum criteria are: (1) The physiological activity should not be disrupted by the measurement process. (2) The measured signal must be high fidelity. (3) The amplifier must be designed to offer high noise rejection.

Plessey Semiconductors are in the process of launching the EPIC electrostatic-voltometer ASIC in the form of a non-contact ECG electrode [11].A prototype of the EPIC product was used to record the data presented in Table 3. Plessey have also commercialised the EPIC technology as a wrist worn heart monitor [17] but have evidently run into problems of distal location and signal discrimination issues, as the product[18] requires the user to touch a conductive pad with a finger from the opposite hand, thereby providing maximal electrode displacement and offering an increased signal recovery magnitude.

A further alternative to capacitive coupling to allow detection of the changes in the body's electric field, is a proximal impedance spectroscopy technique described in the industrial patent Lynn et al. US0178902A1 [19]. Although the spirit of the patent is biased toward the industrial monitoring of carbon fibre composites, the technique may lend itself to be effective for the detection of small changes in the body's electric field. Essentially, the system uses several transformer windings, displaced along a continuous ferrite core, to form a magnetic amplifier. The core is swept to determine its resonant frequency. The amplitude and frequency of the natural resonant frequency (F_0) are indicative of the instantaneous shunt capacitance (C_p) and shunt resistance (R_p) of the proximal body. It is evident that this technique, although requiring substantial development, may also be capable of detecting an ECG without the requirement for body contact or a reference electrode.

V. CONCLUSION

The opinion that distal limb recovery of an ECG is achievable using technology available today is valid and supported by the data presented in this paper. A real-time extraction algorithm, utilising an empirical methodology, although processor and memory hungry, is achievable given the recent advances in portable computing. Today's microprocessors are developed specifically for mobile applications and are capable of 10e+8 instructions per second or better. Quad core offerings from Intel and ARM, to name but a few, have introduced the concept of parallel computing into the mobile world. Massive increases in the capacity of flash memory means that a device capable of running an empirical decomposition algorithm and storing months of data on a non-volatile media could be manufactured for a modest cost.

Improvements in silicon manufacturing capability offer extremely low power integrated circuits to the market. Low power also means low internal noise, allowing for use in very low signal amplitude applications such as distal site ECG monitoring.

As with the driving technology (smart phones), battery capacity will be the ultimate confounding factor. Long term continuous monitoring will require significant battery capacity. Until such times as battery technology catches up with the demands of portable computing, a redundant cell design would allow for hot swapping without an interruption in recording.

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