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An exploration of behind-the-ear ECG signals from a single ear using inkjet printed conformal tattoo electrodes

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***Abstract*— Wearable sensors placed behind-the-ear are emerging as being very promising for unobtrusive long term monitoring. Factors such as gait, electroencephalography (EEG), and ballistocardiography (BCG) can all be measured from behind-the-ear in a socially acceptable hearing aid based form factor. Previous works have investigated the recording of electrocardiography (ECG) from the ear, but generally with one electrode placed some distance away from the ear itself. This paper uses recently introduced *tattoo* electrodes to investigate whether ECG components can indeed be measured from behind a single ear. Compared to a reference photophelsmography (PPG) device we show that the fundamental heart beat frequency is present in behind-the-ear ECG only in half of the cases considered. In contrast the second harmonic is present in all records and could allow the extraction of heart rate to within a few beats-per-minute accuracy. Further signal processing work is required to allow the automated extraction of this, particularly when working with short time windows of data, but our results characterize the signal and demonstrate the principle of behind-the-ear ECG collected from a single ear.**

I. INTRODUCTION

Wearable sensors are now becoming widely known and available for a range of health conditions [1]. It is now relatively common to record parameters such as activity, heart rate, and galvanic skin response from wrist locations, and a wide number of commercial devices from the fitbit to the Empatica E4 are available commercially. Nevertheless, a number of barriers to their widespread use remain, principally around accuracy [2], the need for constant recharging [3], and the level of *invisibleness* for discrete, socially acceptable monitoring, particularly over very long time durations [4]. To overcome this, significant work has been carried out investigating the monitoring of bio-signals from non-conventional parts of the body. Recently a number of works have proposed the ear as being an excellent site for unobtrusive long term monitoring [5]. Devices can be either inside-the-ear [5] or behind-the-ear [6] with both locations easily integrated into standard hearing aid casings. In addition many different sensing modalities are possible [5]. Works have demonstrated gait monitoring [7], ballistocardiography (BCG) [8], electroencephalography for brain monitoring [6], and photophelsmography (PPG) for heart rate [8].

There has also been interest in recording the electrocardiogram (ECG) from ear locations [9]. While heart rate can be obtained from the PPG, in principle ECG could allow heart rate variability to be measured (of interest in a range of clinical conditions from myocardial infarction to diabetic neuropathy [10]) and morphological components (such as P and T waves) to be observed. A number of works have thus investigated ear based ECG monitoring previously. [11] placed one ECG electrode behind-the-ear, and a second electrode lower down on the body, below the neck, and showed a clear ECG trace. However, this electrode montage would require the electrodes to be physically far apart, with wires to connect them and hence limiting wearability. Recording ECG components with electrodes only on the head is much more challenging [12] as the electrical signals from the heart are significantly attenuated as they pass through the physical constraints of the neck. Very recent modeling has investigated this signal attenuation in detail [12] and a number of recent works have attempted to measure ECG components from electrodes placed only on the head. [13] presented a *smart helmet* with electrodes on the forehead and cheeks which could measure ECG, but not as inconspicuously as when electrodes are placed behind-the-ear. [14] successfully recorded ECG from ear only locations, but required electrodes behind both ears with these connected together by wires, again reducing wearability.

To our knowledge the only works to investigate ECG from behind a single ear are the papers from [9]. However, even these place one electrode on the "*posterior upper middle neck*" [9], relatively far down from positions usually covered by a hearing aid. In addition, the ECG was not used directly for measuring heart rate, but combined with BCG. Thus, despite the high potential for unobtrusive ear based sensing the topic of behind-the-ear ECG is significantly underexplored. In this paper we present a preliminary investigation into the collection of ECG signals from electrodes present behind one ear only, with the electrodes positioned close to the ear. Recently we introduced *conformal* electrodes which use non-permanent tattoo-like substrates to connect directly to the skin and can maintain a high quality connection to the body for many days at a time [15]. As they follow the contours

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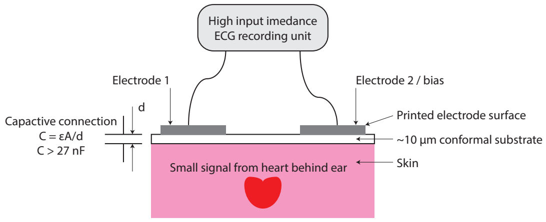

Fig. 1. Our electrodes maintain a capacitive connection to the body with an adhesive conformal substrate behind the entire electrode surface. This increases the surface area available for signal collection.

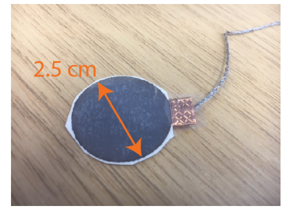

Fig. 2. Example inkjet printed ECG electrode with a sewn in conductive fabric for connecting to conventional ECG recorder.

of the skin they get a much higher contact area giving high Signal to Noise Ratios (SNRs) even at very small sensor sizes. We make use of these to characterize the ECG signal collected from behind-the-ear.

Section II overviews the design and manufacture of our electrodes and the methods used for collecting electro-physiological signals from behind-the-ear. Section III presents our results which show a strong second harmonic of the heart beat frequency is present and can be used to extract the heart rate to within a few beats per minute compared to a reference PPG device. Conclusions are given in Section IV.

II. METHODS

A. *Inkjet printed conformal tattoo electrodes*

To collect the small amplitude ECG signals from behind-the-ear we made use of our inkjet printed ECG electrodes introduced in [15]. These consist of a printed Silver nanoparticle layer on a conformal substrate with an adhesive film placed over the electrode surface to provide attachment to the skin. This gives a capacitively coupled electrode connection, as shown in Fig. 1. Importantly the substrate provides adhesion under the entire electrode surface. As a result, for the same size of total electrode we obtain a much larger sensing area as there is no need for an additional adhesive area outside of the main electrode. In contrast, standard ECG electrodes have a central Ag/AgCl disc for sensing, which is then surrounded by a large area of adhesive material which does not contribute to the signal collection. Our approach is highly beneficial as electrode noise is inversely proportional to the area of the electrode, and there is only a limited amount of hair free space behind-the-ear for doing sensing.

The electrodes are inkjet printed using an in-house process with three layers of electrically conductive Silver nanoparticle ink, discussed in [16]. The substrate is temporary transfer tattoo inkjet paper from [17]. The wanted electrode shapes were drawn in Adobe Illustrator and exported as bitmap files. To manufacture the wanted shape bitmap patterns were processed using a quadrant pixel mask in the GNU Image Manipulation Program (GIMP). The masks were designed to remove 75% of the image pixels reducing the amount of ink printed in any one layer. Silver nanoparticle ink suspension (736465 Sigma-Aldrich) was printed using a 10 pL print head (DMC-11610) on a Dimatix DMP-2800 inkjet printer (Dimatix-Fujifilm Inc., USA). Each quadrant pattern was printed twice in succession onto temporary tattoo paper heated to 60 °C to form one complete image. This was then repeated twice more to yield a three layer image. Finally, the paper was heated to 150 °C for 30 minutes to sinter the metal layers. After printing, the adhesive film layer was placed over the electrode surface to provide a firm attachment to the skin. Upon application to a subject the backing paper of the temporary tattoo transfer material was removed by wetting, leaving behind the printed ink a 10 μm thick substrate.

In [15] we connected the electrodes to the ECG amplifier by using standard ECG cables held on to the electrodes using a Silver loaded ink. This was a suitable method for easy prototyping, but the attachment of the wire was severely limited, falling out long before the electrode itself lost adhesion to the body, and introducing a range of connection artifacts [15]. In this work we have improved the connection by using a Silver platted conductive yarn (Kitronik, Nottingham, UK) as the wire. This is sewn through the ECG electrode once it has been printed and then encapsulated in a copper tape (3M, Japan) to protect the sew points. The other end of the yarn is connected to a standard ECG snap connector. To date this has proved to be a very robust method of wiring up the electrodes, with the yarn being very light and adding little tension which might cause the electrode to disconnect. A picture of a final electrode is shown in Fig. 2.

B. *Bio-signal collection*

For measuring the ECG we used a high quality two electrode ECG unit from CamNtech (Cambridge, UK). This requires no explicit third/ground/driven right leg electrode, allowing us to place just two electrodes behind-the-ear and easing set up in the hair free space available. Two electrodes were placed on the right ear, as shown in Fig. 3. A full circle electrode was used for behind the lower part of the ear, approximately over the mastoid. A semi-circular electrode was used higher up on the ear.

13 records from two subjects were collected where subjects were asked to sit still for 2 minutes to allow an ECG recording to be carried out. From these 1 minute of artifact free data was selected for analysis. For comparison purposes a wearable PPG device (Empatica, Boston, USA) was worn on the wrist to allow a reference heart signal to be measured. Care was taken to use an optical reference device as if using two ECG units the ECG common mode driving from one unit may interfere with the common mode as seen by the other unit, biasing the results. All ECG recordings used a 10 bit resolution, 1024 Hz sampling rate, downsampled to 256 Hz with a 50 Hz powerline notch filter, and 0.16–5 Hz band limiting prior to analysis. The institutional review board in Manchester have approved Dr Casson to perform ECG measurements.

Fig. 3. Illustration of the electrode placement behind the right ear.

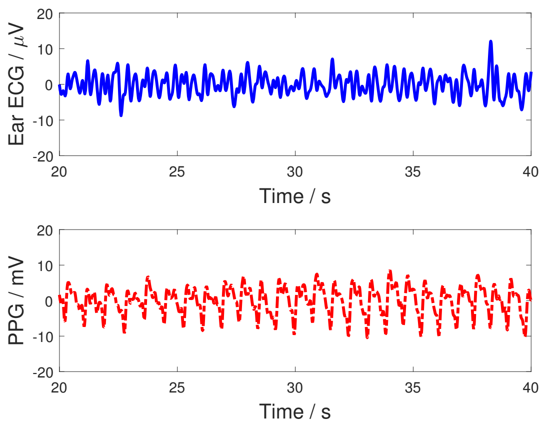

Fig. 4. Example time domain traces for the ear ECG and reference PPG.

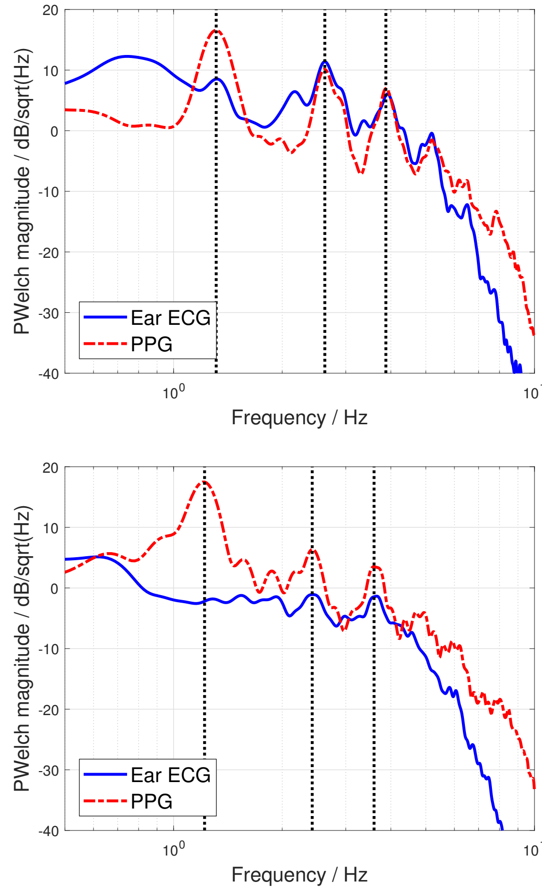

Fig. 5. Welch transforms applied to the ear ECG and reference PPG data for two different records. (Top) Record with fundamental, 1st and 2nd harmonic peaks present. (Bottom) Record with no fundamental ear ECG peak present.

III. RESULTS AND DISCUSSION

Illustrative time domain signals for the ear ECG and reference PPG are given in Fig. 4. Each heart beat is clearly seen in the PPG trace, as would be expected, but this does not correspond to any readily discernible time domain feature in the ear ECG trace. Fig. 5(top) shows the result of a Welch transform, which averages multiple Fourier transforms together, applied to one minute of the collected data. This is calculated using 8 s windows of data with 6 s overlap between each periodogram. The averaging increases the Signal-to-Noise Ratio (SNR) present and results in clear peaks in the frequency domain of the ear ECG data. These align very closely with the peaks of the reference PPG, with peaks for the fundamental frequency, first harmonic and second harmonic easily discernible.

However, the above result is not replicated in all of our collected records. Fig. 5(bottom) shows an example where peaks for the 1st and 2nd harmonic of the heart beat frequency (as determined from the PPG) are present, but there is no peak which corresponds to the fundamental heart beat frequency. This is a common finding across many of the recordings. Table I shows which frequency peaks are seen in the different records and, when present, the difference between the peak frequency for the reference PPG and the ear ECG trace. No fundamental component is present in nearly half (6/13) of the collected ear ECG traces. In contrast the first harmonic can be seen by eye in all of the collected records. The average between this peak extracted from the PPG and extracted from the ear ECG is 0.0444 Hz, which would correspond to an error of 1.3 beats-per-minute if this peak was used for estimating the heart rate.

To estimate the SNR present we have used the ECG processing toolbox from [18] to determine the mean heart beat present in the time domain. The well known Pan-Tompkins algorithm is first run on the raw ear ECG data to extract an initial estimate of potential heart beat locations. The time domain ECG trace is then segmented between these peaks and each of the segmented time sections averaged together. An example result from doing this is shown in Fig. 6 and in all but one of the records a very clear average beat can be extracted. The SNR of this is included in Table I. The SNR present is in general low, with the maximum value present being 12.4 dB. We have been able to extract signals by relying on averaging together multiple segments (in either the time or frequency domain) to allow the heart information to be seen. We use one minute sections of data for this, but recognize this is unlikely to be a practical duration for out-of-the-lab experiments. For comparison, typical PPG smartwatch measures of heart rate use 8 s windows of data, allowing rapid changes in heart rate to be captured. In addition, we currently do not consider traces with artifacts

TABLE I

DIFFERENCE IN PEAK FREQUENCY BETWEEN THE EAR ECG AND PPG REFERENCE. (NP = PEAK NOT PRESENT.) THE SNR MEASURED IN THE TIME DOMAIN IS ALSO GIVEN.

Record	Fundamental / Hz	1st harmonic / Hz	2nd harmonic / Hz	SNR / dB
1	0	0	0	5.8
2	NP	0.0781	0.0312	11.6
3	0.0625	0.0781	0.0156	8.1
4	0.0937	0.0156	0.1094	2.9
5	NP	0.0469	NP	5.4
6	0.0157	0.0625	0.0157	NP
7	NP	0.0156	0	7.3
8	NP	0.1250	0.0469	8.5
9	0	0.0310	NP	12.4
10	0.0625	0.047	NP	9.5
11	NP	0.0156	0.779	4.4
12	0.0156	0	0.0157	5.2
13	NP	0.0621	NP	7.6

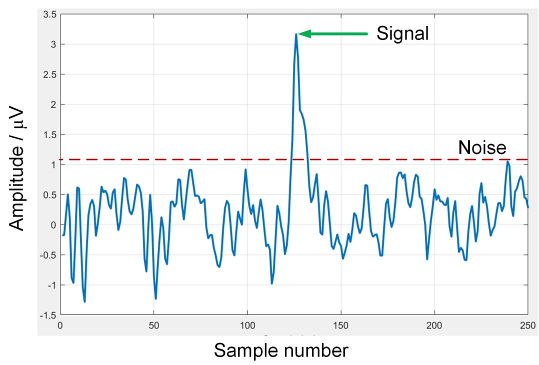

Fig. 6. An average ear ECG heart beat extracted in the time domain and used to calculate the Signal-to-Noise Ratio.

present which will require further signal processing in order to remove them prior to analysis. Nevertheless, all of our results show that there are clear components of the ECG which can be recorded from behind a single ear. This empirically agrees with the modeling recently presented in [12]. We thus show as a preliminary exploration that integration of ECG in to single site devices, such as hearing aid cases, is potentially possible. The next steps are to put together suitable signal processing for enabling the extraction of this heart information using shorter epochs of data and in the presence of motion.

IV. CONCLUSIONS

Previous works have investigated behind-the-ear ECG measurements, but not with electrodes placed behind a single ear. This work has shown that ECG components can be collected from electrodes placed behind a single ear, although they are very small and currently only extracted by averaging epochs of the collected signal together domains. Our results illustrate the potential for ECG to be integrated into hearing aid cases and similar, once suitable signal processing for the automated extraction of the components has been created.

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