Capacitive ECG Recording and Beat-To-Beat Interval Estimation after Major Cardiac Event

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Abstract—Today, heart diseases are the most common cause of death in the U.S. Due to improved healthcare, more and more patients survive a major cardiac event, e.g. a heart attack. However, participation in everyday activity (e.g. driving a car) can be impaired afterwards. Patients might benefit from heart activity monitoring while driving using a capacitive ECG (cECG). However, it is unknown whether cECG is an appropriate monitoring tool for such patients.

In this work, first results from a study including 10 patients having survived at least one major cardiac event are presented. It is shown that cECG can be used to diagnose heart rhythm deviations and estimate beat-to-beat intervals similar to conventional ECG.

I. INTRODUCTION

According to the Centers for Disease Control and Prevention, in 2013 heart diseases (e.g. chronic ischaemic heart disease) were the most common cause of death in the U.S. [1]. Over the years, the treatment of acute cardiac illnesses such as myocardial infarction has much improved [2]. Therefore, the population of patients who survived a major cardiac event has grown.

As a consequence of the major cardiac event, survivors can suffer from two disorders: The risk for another major cardiac event is elevated and patients may suffer from depression [3].

Therefore, patients may be unsure in what activities of everyday life they may safely participate, for example driving a car. Although the crash outcome of a heart attack while driving can be severe, only one per thousand of all traffic accidents is caused by sudden driver incapacitation. Of those, only 8 percent is related to a heart attack [4]. Therefore, myocardial infarction accounts for only 80 per million traffic accidents. Thus, fear of it is hardly rational. However, 76 percent of all drivers involved in a crash caused by cardiac events had already been pre-diagnosed with a cardiac illness [4] and subjective crash anxiety may be high after a major cardiac event.

Therefore, close monitoring of the heart while driving might be beneficial to ensure the driver of his well-being and safety. For disorders of the heart, ECG recording is a well suited monitoring modality. Also, when combined with a heart rate detection algorithm, it can be used as a heart attack predictor as the HR variability diminishes prior to a new heart attack [5].

In prior research, a car seat has been developed that can accurately record ECG signals of the driver by means of integrated capacitive electrodes [6]. Therefore, this technology might be a convenient and unobtrusive monitoring tool for vehicle passengers. However, in automotive environments, this measurement technology has only been tested on healthy drivers. After a heart attack, deviations in the ECG waveform can occur. In case of other cardiac conditions such as AV-block, also rhythm aberrations can be expected. To our knowledge, it has not yet been investigated whether these aberrations can also be observed in a cECG recording. Also, it remains unclear whether proper cECG recording and peak-to-peak heart rate detection might be rendered impossible by such cardiac conditions.

To investigate whether cECG recording for the monitoring of patients after major cardiac event in automotive environments is inappropriate, a clinical trial was conducted. In this paper, we focus on the beat-to-beat interval estimation as an indicator for the proper detection of an ECG.

II. METHODS

A. Trial design

The clinical trial took place at Rosenquelle Rehabilitation Clinic in Aachen, Germany and involved 10 patients due to regulatory limitations. All patients had survived at least one major cardiac event and were in the clinic for rehabilitation. Due to legal and safety consideration, cECG recording in a real world driving task was not possible. Instead, a driving simulator was used. An artificial three lane road was projected on a wall using a digital projector. The patient was sitting in an instrumented car similar to [6] and was able to navigate on the artificial road using a steering wheel and a gas pedal.

In a recording session, the patient had to drive on the road for 30 minutes. While driving, he had to perform a Lane Change Test [8]: Upon request by traffic signs next to the road, he had to frequently change lanes and answer to questions. By that, a more realistic driving situation including concurrent mental/physical driving effort and distractions was created. During the session, cECG data was recorded by means of the instrumented car seat. In addition, a conventional reference ECG (rECG) was recorded as gold standard reference. For safety reason, the patients were under constant supervision by a physician.
B. Measurement system

The instrumented car seat is shown in fig. 1. It compromises the car seat itself with six capacitive electrodes integrated into the back of the seat and a large driven ground electrode (DGE) on the seat cushion. The DGE is used for the elimination of the common mode signal content. The six electrode signals are fed into an instrumentation box, which also drives the DGE. Inside the measurement box, differential ECG measurement channels are formed by subtraction of two of the six electrode signals. The channel signals are filtered (notch-, lowpass-, highpass-filter) to remove noise content and are digitized at a sampling rate of 256 Hz. Afterwards, they are transmitted by USB to a measurement computer. For safety reason, the measurement device is battery powered and an USB isolation device compliant to DIN EN 60601 is used. On the computer, the signals are stored for further processing.

Given six electrodes, a total of five ECG measurement channels are recorded. Using the electrode numbering according to fig. 2, the electrode combinations used for each measurement channel can be seen in table 1.

As gold standard, an ECG integrated into a Weinmann Somnolab sleep diagnostic system was used.

<table>
<thead>
<tr>
<th>Measurement channel</th>
<th>Electrode combination</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1-2</td>
</tr>
<tr>
<td>II</td>
<td>1-4</td>
</tr>
<tr>
<td>III</td>
<td>3-4</td>
</tr>
<tr>
<td>IV</td>
<td>3-6</td>
</tr>
<tr>
<td>V</td>
<td>5-6</td>
</tr>
</tbody>
</table>

TABLE I
MEASUREMENT CHANNELS AND ELECTRODE COMBINATIONS

C. Data Processing

The recorded cECG data was analysed in Matlab. First, digital filters (lowpass, highpass) were applied. No special measure to remove motion artefacts was implemented. Then, R-peak detection was performed on all five cECG measurement channels and the conventional reference ECG channel. As detector an implementation of the Pan-Tompkins-Algorithm [7] was used.

For each measurement channel, R-peaks detected in the capacitive ECG channel were classified in two groups: True positive (TP) and false positive (FP). True positive was set in case a R-peak was detected at the same time also in the reference ECG. To account for slight deviations in the sampling timing of the two measurement devices (instrumented car seat, reference ECG), a tolerance window of 20 ms was given. Otherwise, the R-peak was classified as false positive.

In addition, R-peaks present in the reference ECG but not in the cECG channels (including a 20 ms tolerance window) were classified as false negative (FN). All classified R-peaks were counted.

D. Beat interval calculation

Using all detected R-peaks (TP, FP) in a cECG channel, knowing their sample index and sampling rate, beat-to-beat intervals can be easily calculated by subtraction of consecutive sample indices for all cECG channels divided by the sampling rate.

E. Statistical evaluation

Using the counted R-peaks, two statical values can be calculated. The sensitivity can be calculated as

\[ \text{Sensitivity} = \frac{TP}{TP + FN} \]  \hspace{1cm} (1)

The positive predication value can be calculated as

\[ \text{PPV} = \frac{TP}{TP + FP} \]  \hspace{1cm} (2)

III. RESULTS

A. Subjective inspection of the cECG waveform

Fig. 3 shows a 10 second signal section of the derived waveform as an example. In the lower diagram, the reference ECG is shown. In the upper diagram, a capacitive channel is plotted. A rhythm disorder is observable in the reference ECG (shorter time between two heart actions at time indices 2 sec and 7 sec) which can also be found in the capacitive ECG channel. Therefore, in this exemplary but representative case, the cECG yields the same diagnostic information with respect to heart rhythm aberrations.
B. Beat-to-beat interval estimation

Subjective assessment of heart rhythm aberrations by waveform inspection is tedious and can be biased. Therefore, in fig. 4, beat to beat intervals are plotted against a time index. In the upper plot, the intervals derived from the capacitive channel are shown, in the lower plot, those from the reference ECG.

In the reference plot, a persistent rhythm disorder can be observed: In most cases, the beat-to-beat interval is about 1200 msec, but shorter intervals are also present during the whole recording. The same disorder is also visible in the plot derived from the cECG.

Fig. 5 shows a Bland-Altman plot which can be used to compare the results of the beat-to-beat interval estimation from the cECG and reference ECG. For most cases, the estimation is similar between the two measurements. For these cases, the cECG measurement delivers an equivalent amount of diagnostic information with respect to heart rhythm disorders. However, in particular for shorter beat-to-beat intervals, there is a significant aberration for small number of estimations.

C. Statistical results

Apart from the accuracy of the estimated beat-to-beat intervals, the availability of such data is also important. That is, cECG signal quality must be sufficient and R-peaks present in the cECG signal must be correctly detected. As indicators, the achieved sensitivities for all patients and all channels are shown in table II and the positive prediction values in table III.

The best value for each channel is printed in bold. All values are rounded to two decimal digits.

For most patients, measurement channel III is the best channel regarding sensitivity as well as positive prediction.
TABLE II
R-PEAK DETECTION SENSITIVITY FOR ALL PATIENTS AND MEASUREMENT CHANNELS

<table>
<thead>
<tr>
<th>Patient</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.57</td>
<td>0.76</td>
<td>0.82</td>
<td><strong>0.88</strong></td>
<td>0.63</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>0.62</td>
<td>0.68</td>
<td>0.76</td>
<td>0.75</td>
<td>0.72</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>0.57</td>
<td>0.78</td>
<td>0.86</td>
<td>0.84</td>
<td>0.73</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>0.73</td>
<td>0.76</td>
<td>0.76</td>
<td>0.73</td>
<td>0.21</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>0.50</td>
<td>0.47</td>
<td>0.36</td>
<td>0.17</td>
<td>0.21</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

TABLE III
R-PEAK DETECTION PPV FOR ALL PATIENTS AND MEASUREMENT CHANNELS

<table>
<thead>
<tr>
<th>Patient</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.47</td>
<td>0.66</td>
<td>0.79</td>
<td><strong>0.93</strong></td>
<td>0.58</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>0.55</td>
<td>0.70</td>
<td>0.77</td>
<td>0.75</td>
<td>0.73</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>0.49</td>
<td>0.69</td>
<td>0.81</td>
<td><strong>0.82</strong></td>
<td>0.68</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>0.63</td>
<td>0.66</td>
<td>0.77</td>
<td>0.74</td>
<td>0.66</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>0.50</td>
<td>0.47</td>
<td>0.36</td>
<td>0.31</td>
<td>0.30</td>
<td></td>
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</table>

For seven out of 10 patients, sensitivity and positive prediction value are larger than 0.7. However, for three patients, these values are rather low which presumably originates from a individual body morphology. For patient F, channel III exhibited a very high sensitivity and was therefore chosen for demonstration in the preceding section.

IV. OUTLOOK

Future work should concentrate on the improvement of the availability of correctly detected R-peaks. It should be noted that disturbances, for example motion artefacts, are not present in all channels at the same time. Preliminary inspection of the data revealed that in many cases at least one - but not always the same - channel has sufficient signal quality for correct R-peak-detection. Therefore, data fusion should be investigated as an approach to improve sensitivity and positive prediction value. Also, individual body morphologies leading to reduced sensitivity and positive prediction values should be investigated. Furthermore, a more realistic driving situation should be created, e.g. by use of an advanced driving simulator capable of displaying other traffic participants.

ETHICS STATEMENT

The Institution’s Ethical Review Board approved all experimental procedures involving human subjects under the reference code EK 104/14.

REFERENCES