Case study of ECG signal used as a reference signal in optical pulse transit time measurement of blood flow – The effect of different electrode placements on pulse transit time

Teemu S. Myllylä*[a], Erkki V. Vihriälä[a], Vesa O. Korhonen[b], Hannu S.S. Sorvoja[a]
[a]University of Oulu, Optoelectronics and Measurement Techniques Laboratory, Oulu, Finland;
[b]Oulu University Hospital, Department of Diagnostic Radiology, Oulu, Finland

ABSTRACT

The electrocardiography (ECG) signal is often used as a reference signal when calculating pulse transit times (PTT) measured by photoplethysmographic (PPG) sensors. In addition, ECG measurements are widely used in clinical health monitoring. In clinical measurements, small changes in the time delays of R waves in relation to blood flow pulsations between each ECG measurement are not relevant. In most cases, they would not even be observed, due to the rather low sampling rates used in clinical ECG devices. However, in PTT measurements, where time delays are measured with an accuracy of milliseconds, the placement of ECG electrodes can have a distinct effect on the results.

This paper presents case studies of ECG signals measured simultaneously and independently by two ECG devices. We explore what effect different placements of ECG electrodes have on the R wave of the QRS complex and how it should be taken into account when used as a reference signal in pulse transit time measurements of blood flow. Additionally, we study what kind of ECG electrode placements are most suitable for PTT measurements.

Keywords: Heart pulse, photoplethysmograhp, pulse transit time, electrocardiography, EKG, ECG

1. INTRODUCTION

Electrocardiography (ECG) is commonly used in pulse transit time (PTT) measurements to provide a reference signal. This method is based on computing the temporal difference between the R wave of the QRS complex of the ECG and the beginning of the following pulse wave measured by photoplethysmography (PPG) [1, 2, 3].

However, PTT also relates to non-invasive blood pressure measurements, since a correlation exists between PTT and blood pressure fluctuations [4, 5]. Correlation analysis has proven useful, for example, when compared to BP measurements by cuff-based methods [6]. Nevertheless, to our knowledge, there are not many studies assessing the accuracy of the ECG signal itself, especially in relation to ECG electrode placement, and whether it has an effect on the accuracy of PTT measurements. This is probably because the time position of the R wave of the ECG signal with regard to PTT measurements is assumed to be the same regardless of electrode placement.

This paper presents experimental measurements of ECG signals at various electrode placements. Measurements at a high sampling rate indicate that the placement of ECG electrodes can have a certain impact on the position of the R wave in the time domain. This effect takes the form of small time delays of the R wave pulse between different ECG measurements, when electrodes are replaced between the measurements and the placements are not exactly identical. This can be relevant, particularly when accurate time domain determination of the R wave is required as a reference in determining the pulse transit time of blood flow. Additionally, we studied what electrode placements are most suitable for use in pulse transit time and velocity measurements.

*teemu.myllyla@ee.oulu.fi; phone 358 8 553 2762; fax 358 8 553 2774

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2. METHOD OF MEASUREMENT

In our experiments, ECG signals were measured simultaneously and independently by two ECG devices. Both ECG electrodes and their amplifiers were identical. Concurrently with the ECG measurement, heart pulse waves were measured at various sensor placements by PPG sensors. As a reference measurement, also a Finapres device was simultaneously measuring PPG and blood pressure from the finger tip. PPG was measured to estimate the effect of possible R wave delays on PTT.

To verify the accuracy of our ECG measurements, a verification measurement was initially conducted on every person. Figure 1 shows the electrode placement used in this measurement (on the left). This placement provided a reference, when the electrodes of the other ECG device were moved to a different location for each measurement. Pulse responses of both ECGs were measured independently and simultaneously. Moreover, the amplifiers of the electrodes were swapped between measurements 1 and 2.

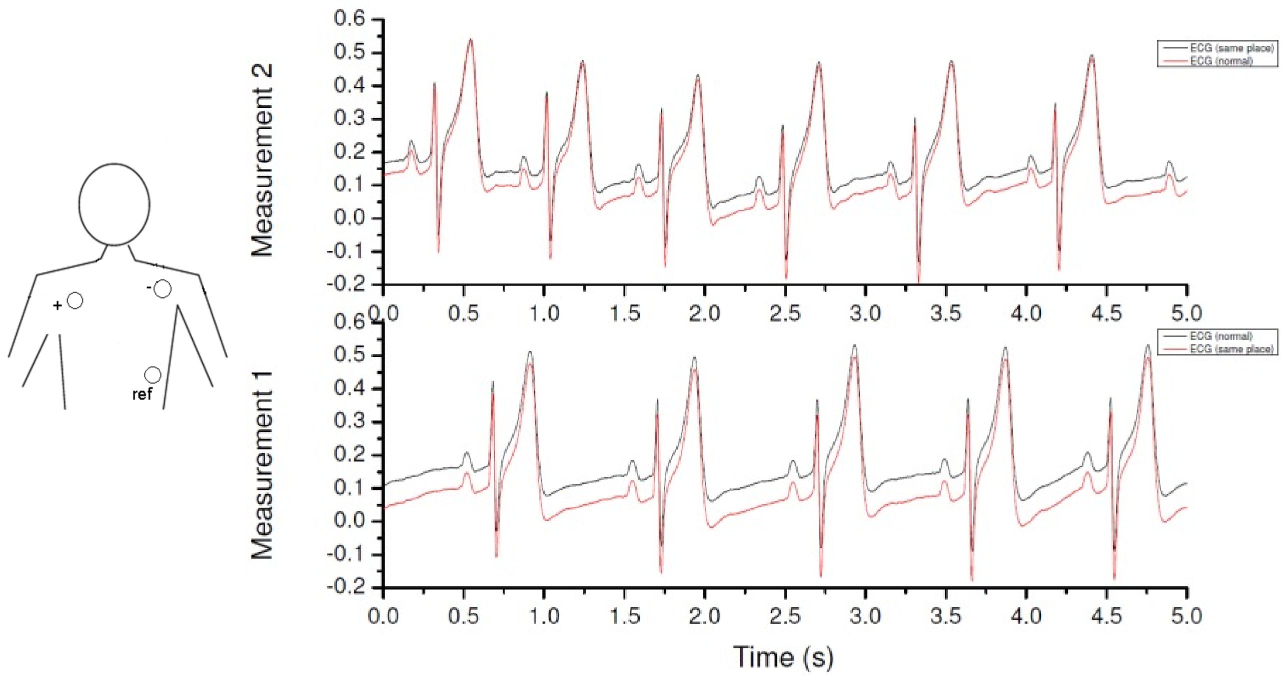

Figure 1. Verification measurement. Electrode placement shown on the left. Both ECG devices use same electrodes in verification measurements 1 and 2. As assumed, the recorded pulses are identical.

In subsequent measurements, all electrode placements were measured twice by swapping the amplifiers of the electrodes (marked between the measurements n.1 and n.2). This was done to ensure that the amplifiers did not affect signal responses. The sampling frequency used in the measurements was 40 kHz, and each measurement continued for about one minute. Possible time delays between the R waves of ECG signals obtained from different electrode placements were recorded while test subject was sitting still. Naturally, both ECG signals were measured simultaneously by the two ECG devices. Analogue signals received from the ECG devices were collected by a National Instruments data acquisition card and processed using LabView software. Data analysis was performed using Matlab and Origin software.

2.1 Conducted measurements

All in all, the effect of six different electrode placements was measured on three healthy test persons. To ensure easy repeatability and comparison of measured data between test persons, the position of only one electrode (+ electrode) of the other ECG was changed. However, we also studied how delays were affected by changing the placement of all electrodes.

Figure 2 shows the electrode placements used in the measurements. Throughout the entire measurement, the other ECG device continued measuring in the same way, using the same electrode placement.

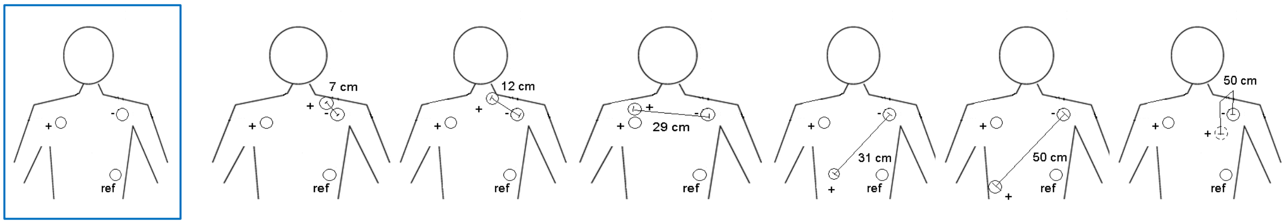

Figure 2. Electrode placements used in the measurements. In each measurement, only one of the electrodes (+ electrode) was moved to a different position. The placement of the three electrodes of the other ECG device was always the same, as shown in the figure on the left. Likewise, for the other ECG, the remaining two electrodes (+ and ref) were always in the same position. In the placement shown on the right, the + electrode is placed on the person's back.

2.2 Calculation of time delays between R waves

Two analysis methods were used to calculate time delays. In the first method, R wave peaks were identified by searching for the maximum value of each time interval in both synchronously measured ECG signals. Next, delays between the corresponding R wave peaks of these two ECG signals were calculated. To evaluate the reliability of this type of analysis, we also tested another method for calculating delays. In this method, signals were divided into parts, and the cross-correlation between the signals was checked for each part. The correlation function revealed the delay for each part.

Table 1 shows a comparison of the delay calculation results of both methods for ECG signals containing interference. Furthermore, signal responses corresponding to Table 1 are shown in Figure 3, representing 24 time intervals. As can be seen, due to interference, some of the time intervals contain additional 'maximum' values. This may lead to erroneous identification of the right R wave peak. To exclude such erroneous R wave detection, different threshold values were experimented with. In this figure, the recorded maximums are marked as dots and delays between ECG signals were calculated as a time difference between each peak pair.

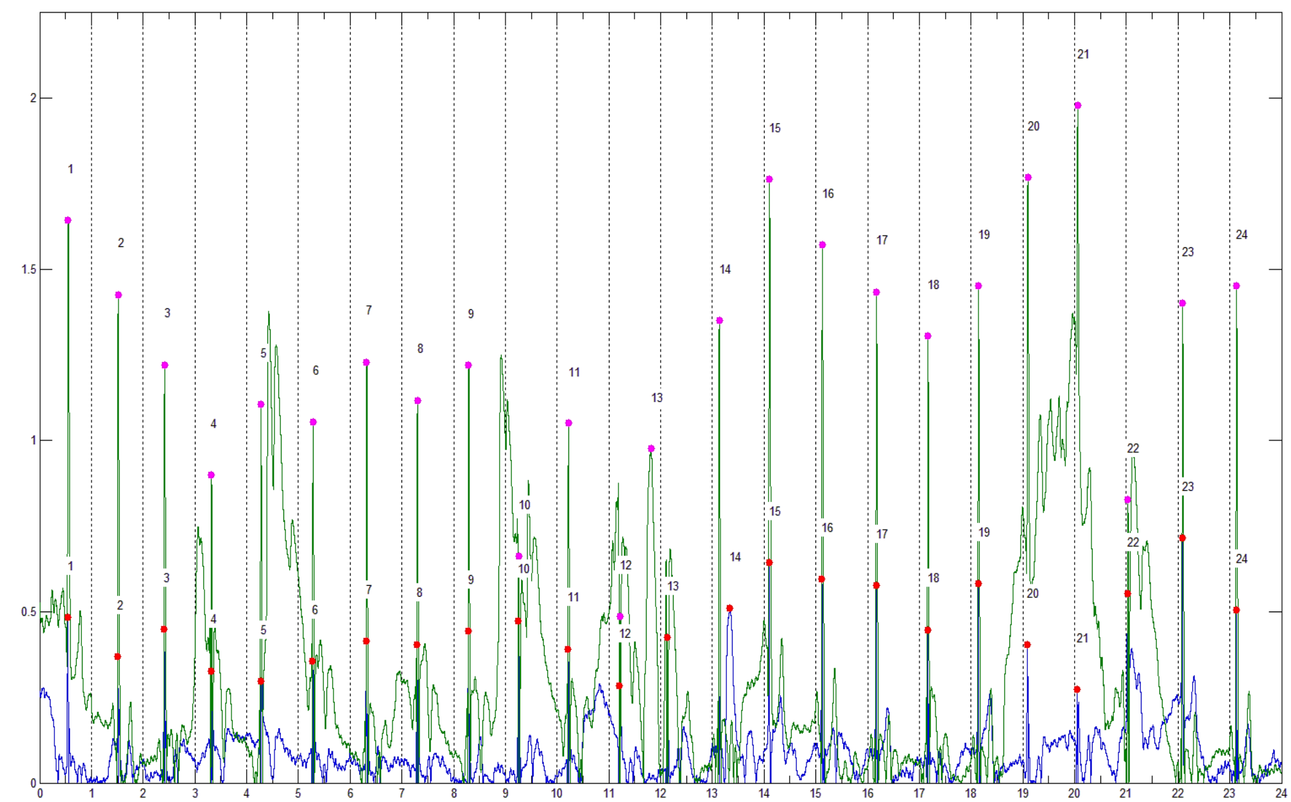

Figure 3. Example of an ECG signal response including some interference, using electrode placement shown in Figure 4. Found maximums are numbered and marked as dots. Time delays of the numbered peaks are presented in Table 1.

Table 1. Time delays calculated by two methods. The interval numbers refer to Figure 3. Typical time delays between the corresponding R waves of two ECG signals acquired at different electrode placements ranged approximately from 1 to 10 ms. Erroneous delay results are in bold and coloured with red.

	ECG signal 1	**ECG signal 2**	**Maximum**	**Correlation**
Number of interval	Time of maximum [s]	Time of maximum [s]	Delay [s]	Delay [s]
1	0,688825	0,69895	0,010125	0,0132
2	1,90705	1,9168	0,00975	0,0076
3	3,039675	3,049225	0,00955	0,011875
4	4,182925	4,193175	0,01025	0,0169
5	5,39135	5,4012	0,00985	**0,3409**
6	6,661675	6,671675	0,01	0,01615
7	7,969625	7,97935	0,009725	0,01095
8	9,208725	9,21865	0,009925	0,011975
9	10,459375	10,4696	0,010225	0,016725
10	11,6822	11,692325	0,010125	**0,28345**
11	12,893975	12,9033	0,009325	0,0118
12	14,1439	14,153475	0,009575	0,016825
13	15,306625	14,9143	**0,392325**	**0,299725**
14	16,846125	16,582175	**0,26395**	**0,147325**
15	17,797	17,8073	0,0103	0,016325
16	19,086725	19,0972	0,010475	0,015825
17	20,408875	20,41875	0,009875	0,0149
18	21,663925	21,674275	0,01035	0,011225
19	22,8977	22,907875	0,010175	**0,2453**
20	24,10155	24,1108	0,00925	0,0116
21	25,31665	25,326175	0,009525	**1,093425**
22	26,5444	26,55295	0,00855	**0,274575**
23	27,876075	27,8868	0,010725	0,017125
24	29,192325	29,2031	0,010775	0,01295
Standard deviation			0,09181349	0,236610598
Average			0,03644583	0,121610417

The results for both methods shown in Table 1 are comparable, but the maximum method seems more accurate. The correlation method cannot properly manage signals that are very different from each other, especially when a measurement error occurs (as in interval no. 5). The maximum method seems to always find the narrowest peak and to ignore measurement errors, if they are wide. Narrow errors, however, the method is not able to deal with (magenta marker no. 13). It would probably also have problems, if the searched peaks were attenuated by some error. However, if the ECG signal response contains no or only slight interference, then the maximum method seems to work acceptably.

3. RESULTS

3.1 Comparisons of two ECG signal responses

Figures 4 - 9 show examples of comparisons of two ECG signal responses measured simultaneously using different electrode placements.

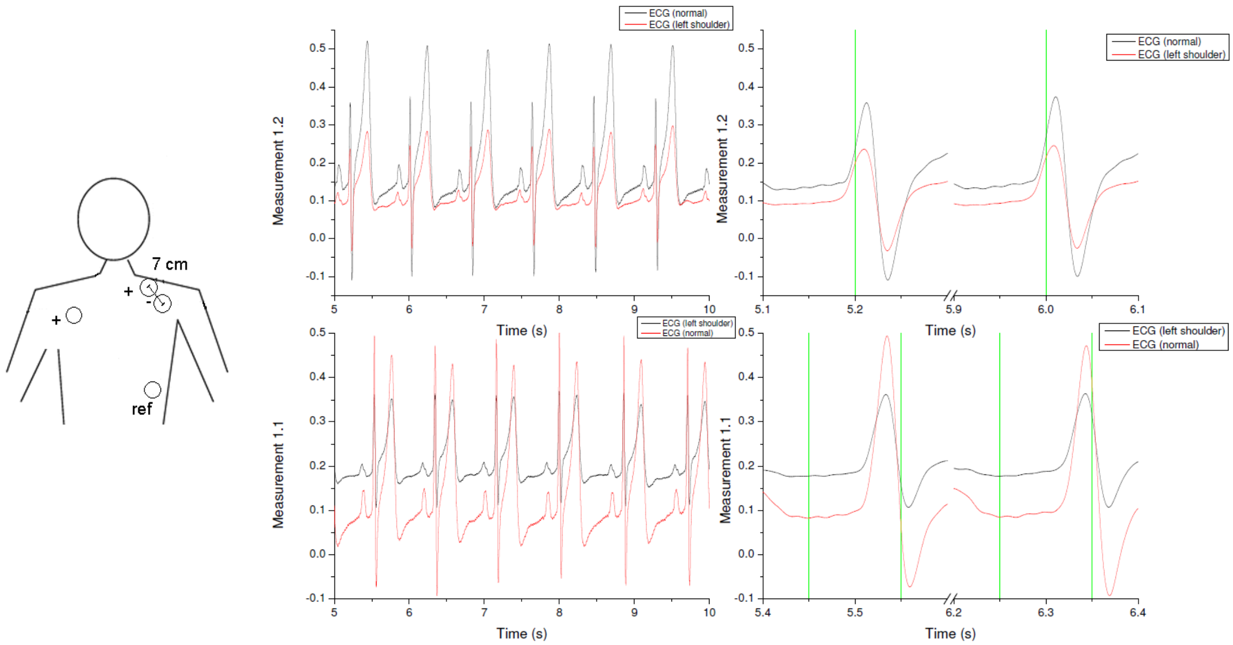

Figure 4. Measurements 1.1 and 1.2. The replaced + electrode was located on the left shoulder and the distance between the + and – electrodes was 7 cm. This caused a delay of approx. 1.5 ms on the R wave, highlighted on the right showing one R wave.

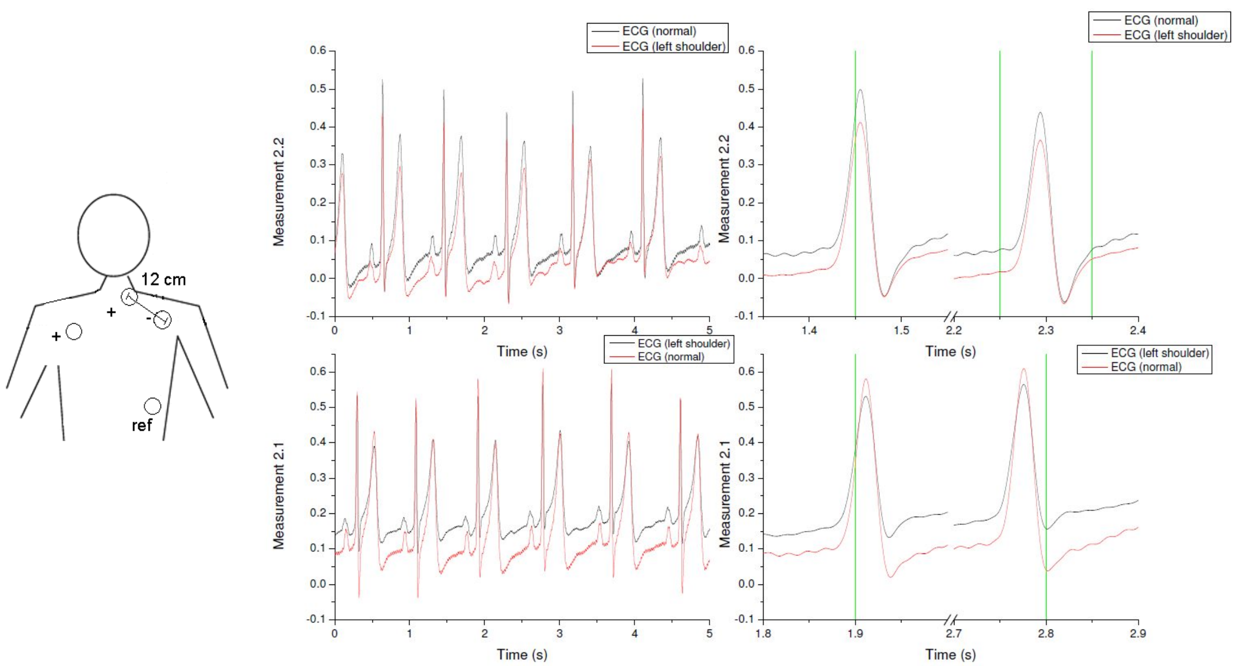

Figure 5. Measurements 2.1 and 2.2. The replaced + electrode was located on the left shoulder (almost on the neck) and the distance between the + and – electrodes was 12 cm. This caused a delay of approx. 0.3 ms on the R wave, highlighted on the right showing one R wave.

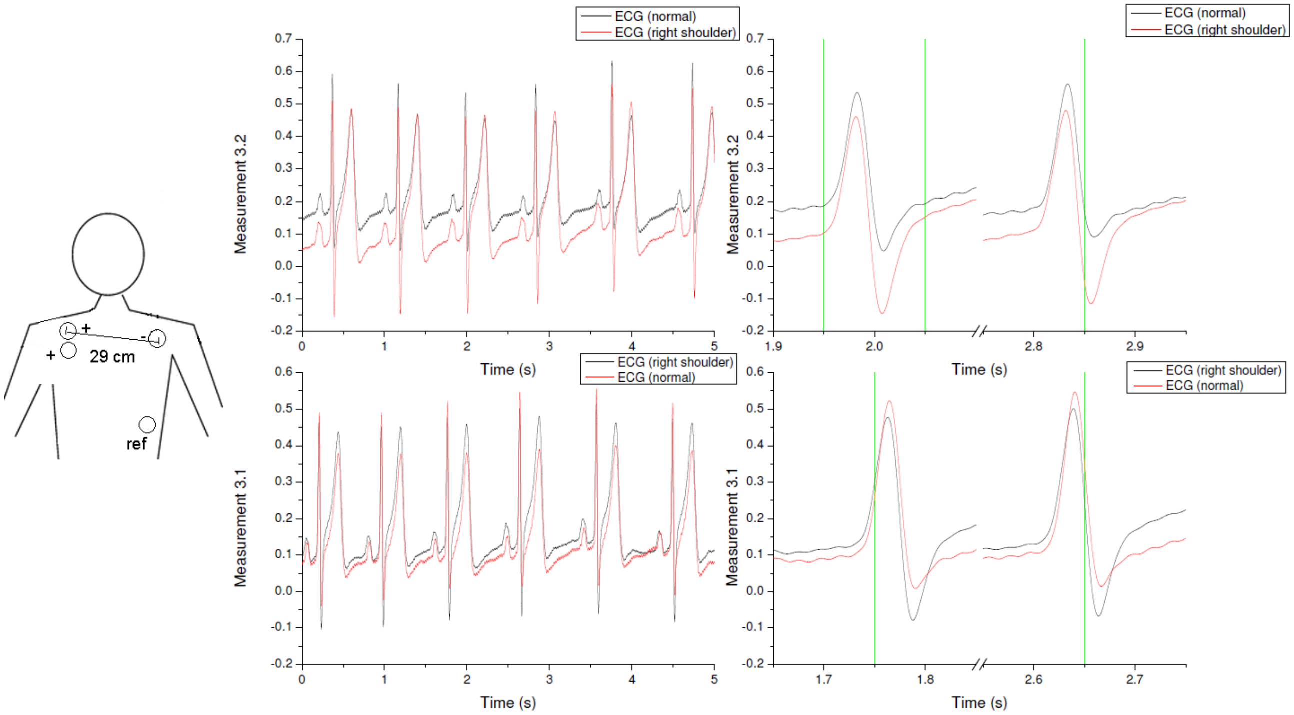

Figure 6. Measurements 3.1 and 3.2. The replaced + electrode was located on the right shoulder and the distance between the + and – electrodes was 29 cm. This caused a delay of approx. 2 ms on the R wave, highlighted on the right showing one R wave.

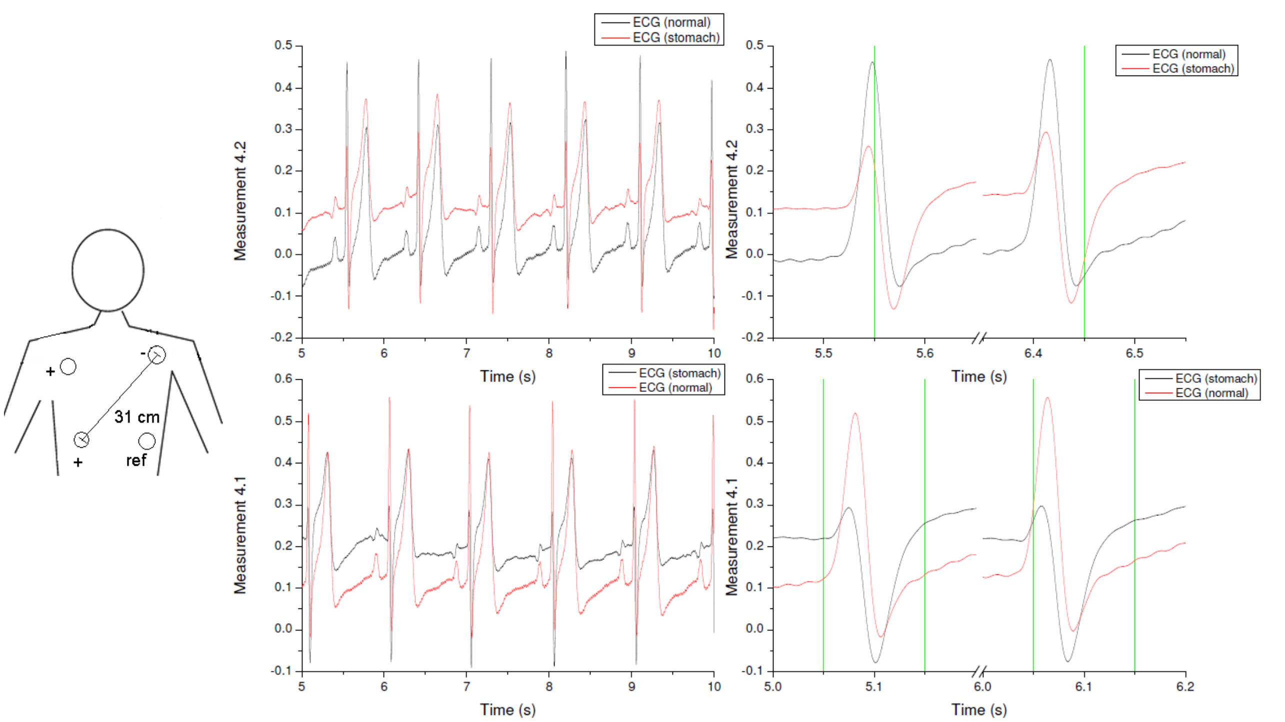

Figure 7. Measurements 4.1 and 4.2. The replaced + electrode was located on the right side of the stomach, and the distance between the + and – electrodes was 31 cm. This caused a delay of approx. 4 ms on the R wave, highlighted on the right showing one R wave.

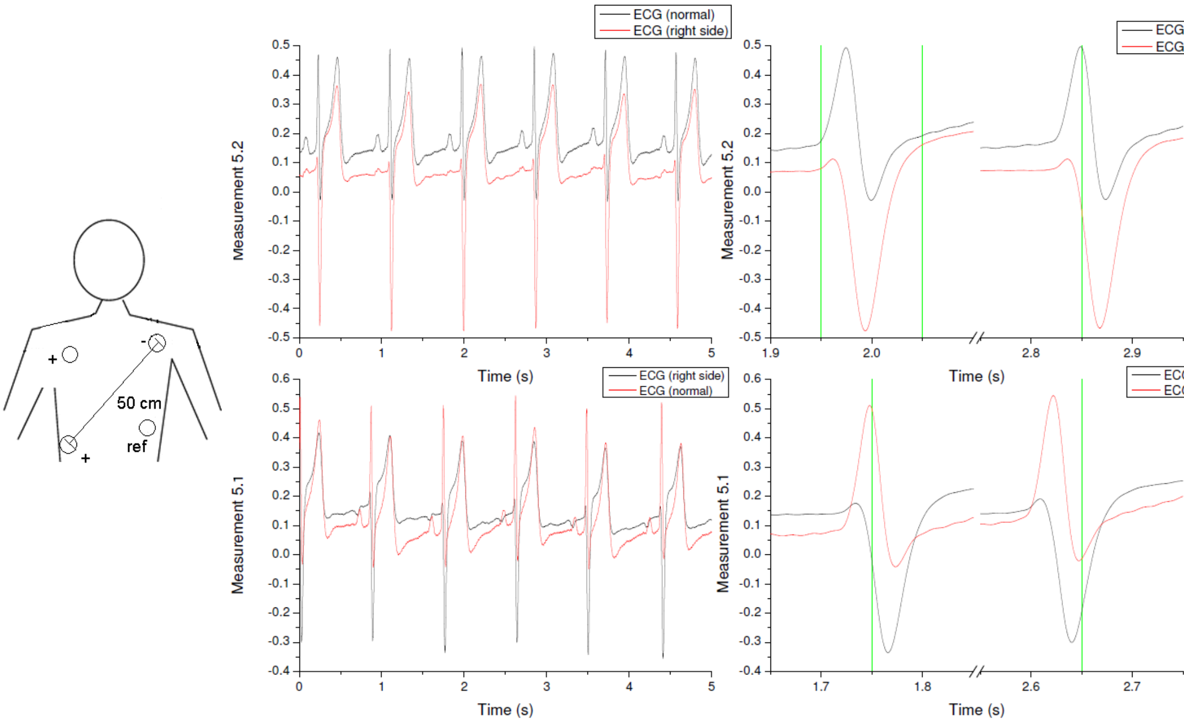

Figure 8. Measurements 5.1 and 5.2. The replaced + electrode was located on the right side and the distance between the + and – electrodes was 50 cm. This caused a delay of approx. 6 ms on the R wave, highlighted on the right showing one R wave.

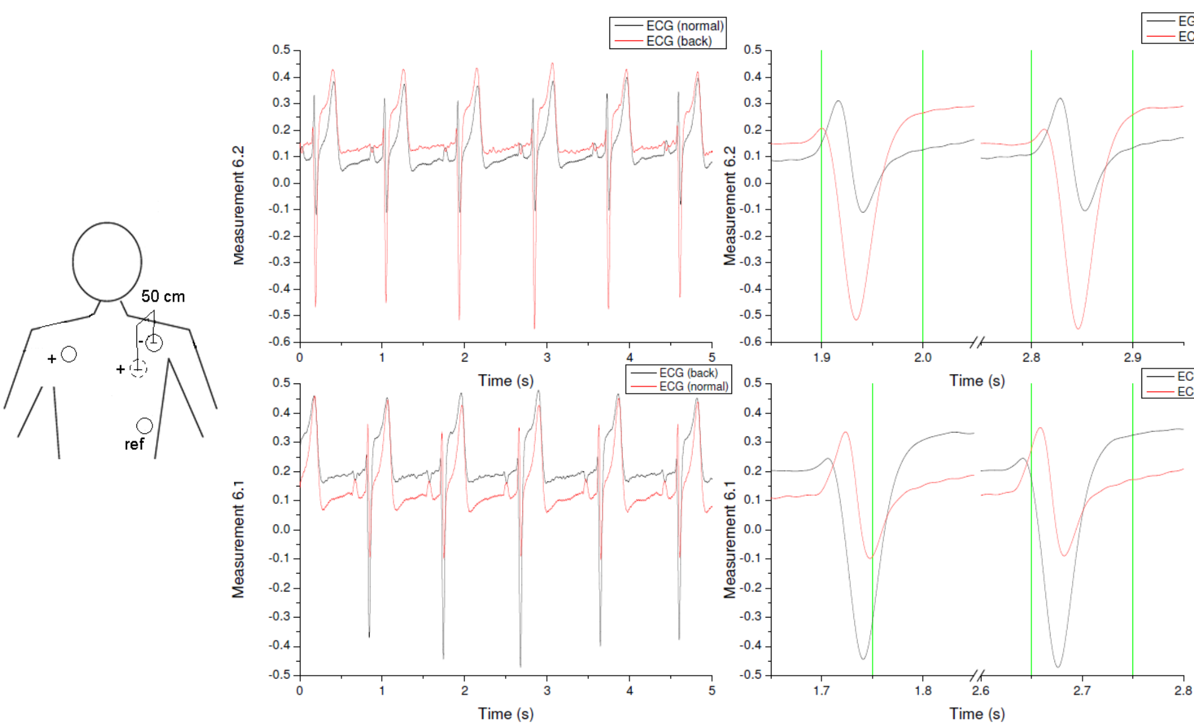

Figure 9. Measurements 6.1 and 6.2. The replaced + electrode was located on the back and the distance between the + and – electrodes was 50 cm. This caused a delay of approx. 10 ms on the R wave, highlighted on the right showing one R wave.

As the presented ECG signals show, three electrodes, as used in the measurements here, allowed us to acquire a clear and sharp R wave for PTT measurements. The R peak was sufficiently good at every electrode placement, but the first three placements on the left in Figure 2 gave a slightly better signal-to-noise ratio than the others.

It is worth mentioning that, besides the EEG cap, some EEG devices also include an electrode that can be placed on the back of the patient. This allows measuring ECG in addition to EEG. However, as shown in Figure 9, in our measurements, this placement gave the lowest quality ECG signal, although it sufficed for PTT measurements. Additionally, this electrode placement produced more delay in the R peaks than the other placements.

3.2 Effect of R wave delays of the ECG on PTT measurements

To study the significance of the effect of R wave delays on ECG in PTT measurements, simultaneous measurements were conducted using three PPG sensors in different places, as shown in Figure 10. One PPG, with a source detector distance of 3 cm, was attached on the forehead to obtain pulsations from deeper within tissue. PPG 2 and PPG 3 measured skin blood pulsations. In this measurement, the placement of ECG1 and ECG 2 electrodes was almost identical, but the corresponding ECG 1 and ECG 2 electrodes were at slightly different distances from each other, as shown in Figure 9. This simulates a normal occurrence in clinical ECG measurements: when electrodes are relocated between measurements, they do not always end up in exactly the same position as before.

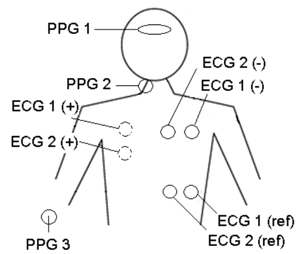

Figure 10. PPG sensors placed on the forehead, neck and right fingertip. Corresponding ECG1 and ECG2 electrodes are placed at a distance of 6 cm from each other.

Figure 11 presents an example of signal pulses in the time domain when PPG sensors and ECG electrodes are placed as shown in Figure 10. Furthermore, Table 2 shows the time positions of R wave maximums calculated for the signals presented in Figure 11.

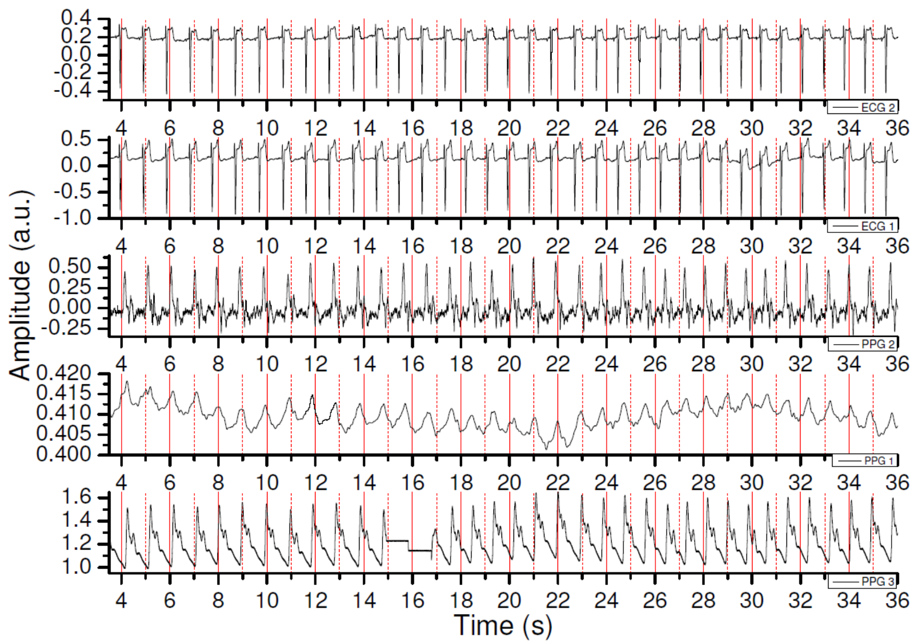

Figure 11. Comparison of measured signals in the time domain.

Table 2. Time point of the R wave maximum of signals presented in Figure 11.

ECG 2 Time of maximum [s]	ECG 1 Time of maximum [s]	PPG 2 Time of maximum [s]	PPG 1 Time of maximum [s]	PPG 3 Time of maximum [s]
3.91823	3.91963	4.1461	4.23173	4.25567
4.87897	4.88	5.10283	5.1957	5.2057
5.8305	5.83367	6.0576	6.13087	6.16137
6.80437	6.80653	7.03533	7.09683	7.14173
7.70623	7.70813	7.93473	8.0422	8.04023
8.6625	8.6645	8.88677	8.95587	8.98803
9.6517	9.6535	9.87167	9.9385	9.9807
10.63723	10.6392	10.87207	10.92807	10.97833
11.5758	11.57807	11.78743	11.87313	11.90523
12.53467		12.75433	12.82513	12.86157
13.53383	13.5358	13.75477	13.83327	13.86373
14.4819	14.48353	14.71517	14.75	14.8231
15.40377	15.40587	15.6326	15.69943	
16.35847	16.3605	16.583	16.62213	
17.30997	17.3125	17.5357	17.60917	17.64547
18.16167	18.16397	18.396	18.42843	18.49933
19.04797	19.05047	19.27297	19.37243	19.3767
19.89093	19.893	20.1335	20.18837	20.2305
20.77397	20.77543	20.99433	21.0494	21.09667
21.68263	21.68457	21.9066	21.98557	22.00673
22.65617	22.65827	22.88667	22.9518	22.9842
23.5474	23.54903	23.77587	23.84847	23.885
24.4339	24.4363	24.65587	24.72787	24.76103
25.31957	25.32137	25.55717	25.60393	25.64893
26.18697	26.18897	26.41817	26.49997	26.52497
26.99797	26.99953	27.23137	27.25	27.33027
27.84493	27.84743	28.0675	28.1101	28.17093
28.68153	28.68323	28.9068	29	29.01093
29.5179	29.5202	29.75257	29.78887	29.8516
30.32403	30.3264	30.56103	30.63617	30.6569
31.16	31.1617	31.37793	31.49993	31.48303
32.0419	32.04457	32.25897	32.33087	32.3636
32.92847	32.93017	33.1498	33.22333	33.2658
33.7698		34.00237	34.06	34.10143
34.6209	34.62243	34.84423	34.8958	34.94127
35.48177	35.48357	35.7142	35.75	35.80893

Figure 11 and the corresponding Tables 2 and 3 indicate that the effect of the time delay between two ECGs is rather small in comparison to the pulse transit time. Thus, the average time delay between ECG 1 and ECG 2 in this measurement was only 2 ms, as presented in Table 3, while the calculated PTT values (time interval between ECG and PPG) were on average 227 ms for PPG 2, 293 ms for PPG 1 and 330 ms for PPG 3. Therefore, according to this measurement, a slightly different replacement of ECG electrodes between two measurements can cause an average error of approximately 0.6 – 0.8% in the PTT result.

Table 3. Comparison of delays between ECG 1 and ECG 2 and between ECG 2 and three PPGs placed as in Figure 9.

	Delay ECG 2-ECG 1 [s]	**Delay ECG 2-PPG 2 [s]**	**Delay ECG 2-PPG 1 [s]**	**Delay ECG 2-PPG 3 [s]**
	0.0014	0.22787	0.3135	0.33743
	0.00103	0.22387	0.31673	0.32673
	0.00317	0.2271	0.30037	0.33087
	0.00217	0.23097	0.29247	0.33737
	0.0019	0.2285	0.33597	0.334
	0.002	0.22427	0.29337	0.32553
	0.0018	0.21997	0.2868	0.329
	0.00197	0.23483	0.29083	0.3411
	0.00227	0.21163	0.29733	0.32943
		0.21967	0.29047	0.3269
	0.00197	0.22093	0.29943	0.3299
	0.00163	0.23327	0.2681	0.3412
	0.0021	0.22883	0.29567	
	0.00203	0.22453	0.26367	
	0.00253	0.22573	0.2992	0.3355
	0.0023	0.23433	0.26677	0.33767
	0.0025	0.225	0.32447	0.32873
	0.00207	0.24257	0.29743	0.33957
	0.00147	0.22037	0.27543	0.3227
	0.00193	0.22397	0.30293	0.3241
	0.0021	0.2305	0.29563	0.32803
	0.00163	0.22847	0.30107	0.3376
	0.0024	0.22197	0.29397	0.32713
	0.0018	0.2376	0.28437	0.32937
	0.002	0.2312	0.313	0.338
	0.00157	0.2334	0.25203	0.3323
	0.0025	0.22257	0.26517	0.326
	0.0017	0.22527	0.31847	0.3294
	0.0023	0.23467	0.27097	0.3337
	0.00237	0.237	0.31213	0.33287
	0.0017	0.21793	0.33993	0.32303
	0.00267	0.21707	0.28897	0.3217
	0.0017	0.22133	0.29487	0.33733
		0.23257	0.2902	0.33163
	0.00153	0.22333	0.2749	0.32037
	0.0018	0.23243	0.26823	0.32717
Min	**0.00103**	**0.21163**	**0.25203**	**0.32037**
Max	**0.00317**	**0.24257**	**0.33993**	**0.3412**
St dev	**0.00042**	**0.00667**	**0.0202**	**0.00579**
Average	**0.002**	**0.2271**	**0.29375**	**0.33098**

In all conducted measurements the average delay between ECG 1 and ECG 2 varied from 2 ms to 10 ms depending on the electrode placement. Therefore, replacement of electrodes caused at highest the average error of approximately 5% in the PTT result. However, in normal occurrences electrodes are relocated between measurements in almost the same position as before in which case the average error seems to be not more than 1 %.

In addition, it is notable to mention that there was also variation with time delays between ECG 1 and ECG 2 in each heart pulse of a single measurement. For example, in Table 3 presented delay values varied from the minimum of 1.0 ms to the maximum of 3.1 ms although standard deviation was only 0.42 ms. Therefore, it seems that PTT values are slightly depended on placement of ECG electrodes also in single measurements. Hence, resolution of ECG measurement is partially dependent on electrode placement.

4. DISCUSSION

The amplitude of the measured potential difference (PD) in the electromagnetic field (EMF) between two electrodes is related to the direction of the EMF vector. The measured PD is proportional to the vector's projection to the line between the electrodes. If, for example, the direction of the vector changes and the amplitude remains the same, both the projection and the measured result change. Also a change in electrode location affects the amplitude (the projection of the EMF vector changes with the direction of the line between the electrodes). Naturally, any alteration in the measured amplitudes may have an effect on the temporal locations of the maximum peak amplitudes.

The direction of the EMF vector with ECG measurements changes widely within one ECG cycle. This can be seen by applying vector cardiography (Figure 12, Figure 13, Figure 14 and Figure 15). Figure 12 shows ECG cycles measured with an Einthoven connection 1 (PD measured between hands) and Figure 13 cycles measured with a Goldberger connection aVF (PD measured between both hands and the left leg).

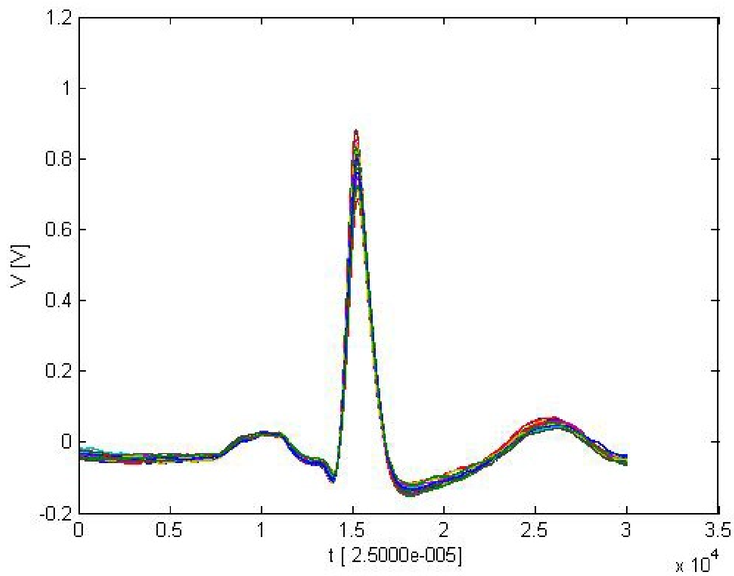

Figure 12. ECG cycles measured with an Einthoven connection 1 (N=30).

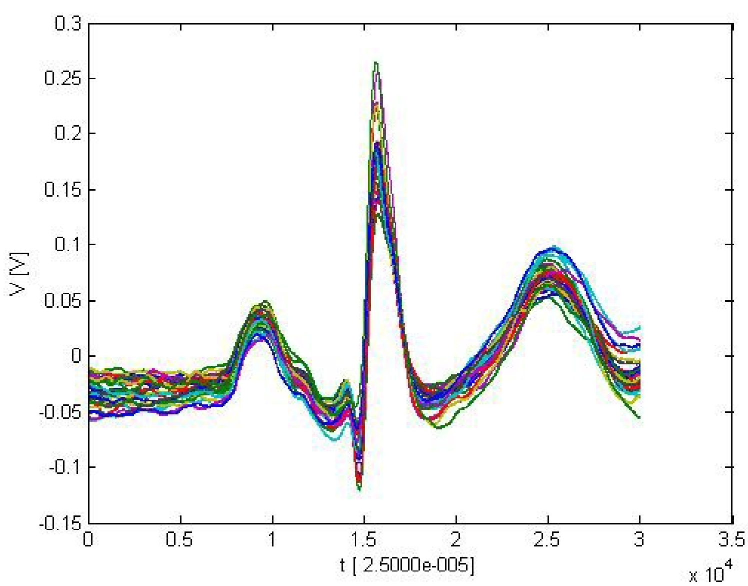

Figure 13. ECG cycles measured with a Goldberger connection aVF (N=30).

Figures 14 and 15 present determined vector cardiograms. These cardiograms were determined by calculating the vector sums of the signals presented in Figures 12 (x-axis) and 13 (-y-axis, signals being inverted). In Figures 14 (all signals) and 15 (calculated average trajectory), the shown trajectories can be considered to be drawn by the peak of the EMF vector with its starting point at the origin. The amplitude of the vector is proportional to the amplitude of the EMF vector, and the direction shows the direction of the EMF. The temporal length of the trajectories is 0.75 s.

These figures show that the direction of the EMF vector varies significantly within one ECG cycle. On the other hand, the direction of the vector during the R-peak's (indicated by the loops in the figures) maximum value varies much less (the bolded line in Figure 15, temporal length being 0.02s). This explains the fact that, even if the temporal position of the R peak changes when electrodes are relocated, these changes tend to be minor.

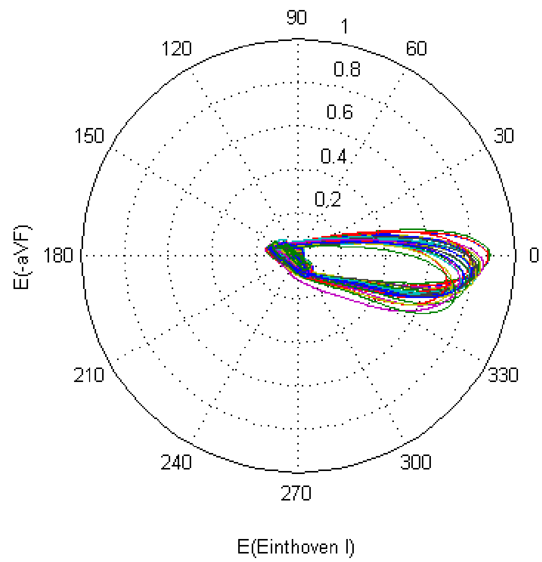

Figure 14. Determined vector ECG cycles (N=30), calculated using the signals shown in Figs. 12 and 13.

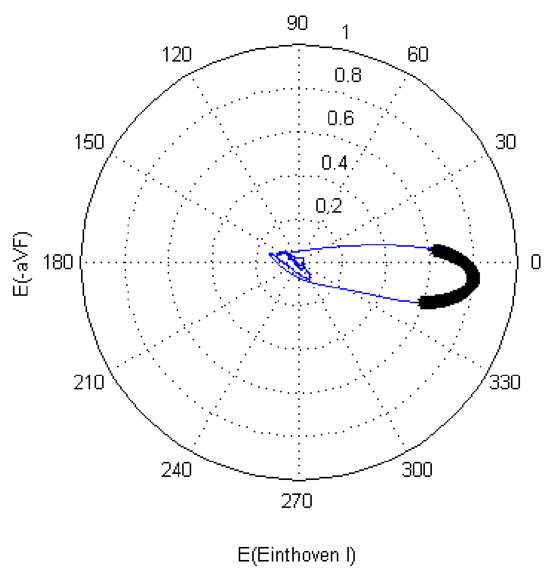

Figure 15. Vector ECG cycle using calculated average signals in Figures 12 and 13. The bolded line in the figure indicates the R peak's maximum value period. The temporal length of the period is 0,02s.

5. CONCLUSION

The results show that the position of the R peak in the time axis depends on the placement of the electrodes used in ECG measurements. Although variations in the time axis are small, they may be relevant in some situations when the R wave of the ECG is used as a reference in pulse transit time measurements of blood flow.

Placing the electrode on the back has a larger impact on the time position of the R wave. Furthermore, it is reasonable to claim that the resolution of the ECG signal in proportion to the time domain can be partially dependent on electrode placement.

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