BASELINE WANDER REMOVAL AND ISOELECTRIC CORRECTION IN ELECTROCARDIOGRAMS USING CLUSTERING

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ABSTRACT

Baseline wander is a low frequency noise which is often removed by a highpass filter in electrocardiogram signals. However, this might not be sufficient to correct the isoelectric level of the signal, there exist an isoelectric bias. The isoelectric level is used as a reference point for amplitude measurements, and is recommended to have this point at 0 V, i.e. isoelectric adjusted. To correct the isoelectric level a clustering method is proposed to determine the isoelectric bias, which is thereafter subtracted from a signal averaged template. Calculation of the mean electrical axis (MEA) is used to evaluate the isoelectric correction. The MEA can be estimated from any lead pairs in the frontal plane, and a low variance in the estimates over the different lead pairs would suggest that the calculation of the MEA in each lead pair are consistent. Different methods are evaluated for calculating MEA, and the variance in the results as well as other measures, favour the proposed isoelectric adjusted signals in all MEA methods.

Index Terms— Baseline wander, isoelectric correction, asystole, 12-leads electrocardiogram, mean electrical axis

1. INTRODUCTION

Baseline wander is a low frequency noise which overlaps with clinically important frequency bands of electrocardiogram (ECG) signals, such as frequencies composed in the ST-segments. A recent comparative study of baseline wander removal [1] concurs with the *Recommendation for Standardization and Interpretation of the Electrocardiogram* [2], with the recommendation of using a zero phase highpass filter with a cutoff frequency of at least $f_c = 0.67$ Hz. Even when the baseline wander is attenuated not all methods correct the isoelectric level of the signal [3]. The isoelectric level, or the baseline, is the reference point to measure wave amplitudes [4, 5]. Therefore baseline wander removal can be regarded as removing low frequency while isoelectric correction is to enforce reference points to 0 V. The isoelectric bias is the amplitude offset of the reference point before constraining. For acute ischemia patients with ST-elevation there exist an inherent isoelectric bias, but it is still useful to correct the baseline to 0 V for parameter measurements.

Ideally, the isoelectric bias is estimated from regions of low electrical activity such as PQ-segment (PR-segment) [6, 4] and the TP-segment [7]. Sometimes the ST-segment can also be used, but due to potential ST-elevation, it is not reliable. In the *International Standard IEC 60601-2-25* [5], the recommendation is to use P-onset and QRS-onset for P wave and QRS complexes respectively. No recommendation for ventricular repolarization is mentioned.

Baseline wander removal methods such as cubic spline interpolation (CSI) [8] and quadratic variation reduction (QVR) [3] correct the isoelectric level by constraining the reference points to 0 V. The methods use knots defined from a fixed location relative to the R peak as reference points. The CSI method would fail in circumstances where only one knot can be drawn from the signal, such as in a signal averaged template. There is, however, a possibility to use P-onset, P-offset, QRS-onset and T-offset as knots [5], but because of edge effects and the difficulty of finding the T-offset [4] it might be better to consider the (local) isoelectric bias to be constant after reduction of the baseline wander, such as highpass filtering, has been performed. Globally to constrain segments or amplitudes to 0 V is the same as baseline wander removal with isoelectric correction, regardless if the baseline wander has been removed prior to the correction of the isoelectric level, due to fluctuation of the amplitudes. The knot locations are very important for the CSI method not to fail. The QVR method uses the same knots as in the CSI method, and may perform well with only one knot [3]. This is a bit questionable since the reference signal used to assess the method in [3] has negligible baseline wander, but there is no certainty that the reference signal has correct reference points enforced to 0 V.

Another method proposed by Stephenson [7] to reduce the baseline wander uses zone segmentation, histogram of amplitude and interpolation (ZHI). In the ZHI method the reference point is estimated using inactive regions and histogram. Because a relatively wide window and constant histogram bins without flexibility is used, the baseline wander might be reduced, however, the isoelectric PQ- or TP-segments are not forced to 0 V. The proposed method can be seen as related to Stephenson's method. Since the PQ-segment, compared to the QRS complex, is slow varying, a local isoelectric bias can be estimated with a clustering in a neighbourhood of the QRS complex. Deriving the isoelectric bias by first finding the PQ-segment imposes two extra variables, wave- onset and offset, which introduces extra error [6] in their location.

Following the adjustment of the isoelectric level, a method to measure the fidelity of the correction is sought. One way is to manually measure the amplitude of fiducial points with respect to the baseline and see if it is reproducible with additive constant noise. This will only test if the amplitude is calculated correctly, and not necessary the fidelity of the correction. A recent published paper on *Invariant Mean Electrical Axis in Electrocardiogram* [9] proposes a method to test the fidelity through calculating the mean electrical axis (MEA). Calculating the MEA is an inverse problem [10] which does not have a unique solution. However, the MEA can be calculated from any pair of leads in the frontal plane, thus any variation of this calculation will be a measurement of fidelity [9] of the isoelectric line correction.

In this work the proposed clustering-based method will be used on a signal averaged template. The signal to noise ratio is presumably high, therefore only the effect of isoelectric correction will be tested. The method will estimate the local isoelectric bias from the PQ-segment.

2. MATERIALS AND METHODS

2.1. Dataset

The dataset which is used in this paper is from the North Sea Race Endurance Exercise Study (NEEDED). The dataset contains approximately 3000 records with duration of 10 s and a sampling frequency of $f_s = 600\,\mathrm{Hz}$. ClinicalTrials.gov identifier: NCT02166216.

2.2. Preprocessing

The ECG signal is preprocessed to remove most of the baseline wander with a simple highpass filter with a cutoff frequency $f_c = 0.67\,\mathrm{Hz}$. The powerline interference and high frequency above $150\,\mathrm{Hz}$ is also removed according to recommendation [2]. Thereafter a signal average is used to find the most common QRS complex and its template. This template either with or without the isoelectric correction is used to calculate the MEA based on the method proposed in [9].

2.3. Finding the Isoelectric Bias

The isoelectric bias is presumed to be constant and is estimated from the PQ-segment. This segment is assumed to be a line. Let I be the set of all points in a PQ-segment. A linear regression will give the line model $y = ax + b$. If the slope is forced to be zero then it can be shown that the estimator of the constant term is:

$$\hat{b} = \frac{1}{K} \sum_{i=0}^{K-1} y_i, \tag{1}$$

where K is the cardinality of the set I, and y_i is the ordinate, amplitude, of the points in I. Thus a zero slope line estimate of the isoelectric level is just the average of amplitudes in the PQ-segment.

Instead of finding the PQ-segment directly, the amplitudes which corresponds to the PQ-segment are found through clustering. Clustering with the Euclidean metric is performed to find the amplitudes. The benefit with Euclidean space (one dimensional) is that translation is an isometry. Therefore to exploit this property the clustering is performed on an ordered set with respect to the amplitude, from lowest to highest amplitude. This ensures that the algorithm gives the same result every time it is performed. Any additional constant shift in the signal does not affect the resulting isoelectric adjusted segment. The clustering is performed in a neighbourhood L of the R peak in the signal averaged template. The algorithm is outlined as:

1. Initiate $i = 0$, $k = 0$ and with cluster $C_k = \{y_i\}$
2. Next calculate the distance $d = \max\{|y - y_{i+1}|\}$, $\forall y \in C_k$.
3. If $d < \epsilon$ then add y_{i+1} to the cluster C_k, else increase k by one and create the new cluster $C_k = \{y_{i+1}\}$.
4. Increase i by one and repeat from step 2.

Step 2 is only one calculation because the elements are ordered. Let the cluster C_{iso} be the cluster primarily having the highest number of elements on the left side of the R peak, and secondly, having the highest total number of elements in the cluster. The isoelectric bias, $\hat{b}$, is estimated by taking the average of the elements in the cluster C_{iso}:

$$\hat{b} = \frac{1}{|C_{iso}|} \sum_{y \in C_{iso}} y, \tag{2}$$

where $|C_{iso}|$ is the total elements in the cluster. To correct the isoelectric level the bias is subtracted from the signal averaged template. The algorithm can be viewed as a simplification of the Douglas-Peucker algorithm in [11].

According to [5] a wave in an ECG signal is defined to have amplitudes of $30\,\mu\mathrm{V}$ ($20\,\mu\mathrm{V}$ [2]) for at least $6\,\mathrm{ms}$. Between global onset and offset of QRS complex, segments that have a duration above $6\,\mathrm{ms}$ and amplitudes do not exceed $20\,\mu\mathrm{V}$ for 3 samples (sampling frequency is not specified) is to be considered isoelectric. Because of this, ϵ should be below $30\,\mu\mathrm{V}$.

2.4. Mean Electrical Axis

The (QRS) mean electrical axis is the net direction (an angle) of the depolarization of the ventricle. The net direction can be calculated from the net potential. There are different definitions of the net potential. Two of them are sum of the amplitudes of R- and S peak V_{rs}, and area under the curve V_{area}. Calculation of MEA is based on the method proposed in [9]. Axis deviation category are determined from criteria in [12] and is shown in table 1.

2.5. Assessment

For comparison with and without isoelectric correction the assessment of the MEA will be done similarly to the comparison in [9], and briefly outlined in the following. Let $G = \{g_{i,j}\} = [\underline{g}_1, \underline{g}_2, \ldots, \underline{g}_N]$ be a matrix of the size (M, N), M is the number of lead pairs and N is the number of records. The entries in G corresponds to a MEA calculation from a lead pair. The row deviation for a row i is defined as

$$D_{r,i} = \sqrt{\frac{1}{N} \sum_{j=1}^{N} \left(g_{i,j} - \mathrm{E}\left\{ \underline{g}_j \right\} \right)^2} \tag{3}$$

where $\mathrm{E}\{\cdot\}$ denotes the expected operator. $D_{r,i}$ will be used for comparison; in particular the average value, i.e

$$\frac{1}{M} \sum_{i=0}^{M} D_{r,i}, \tag{4}$$

as well as the standard deviation of $D_{r,i}$. The row deviation measures the dispersion of a lead pair from the mean [9]. A low average and standard deviation of $D_{r,i}$ is preferable, suggesting that the calculation of the MEA in each lead pair are consistent.

3. EXPERIMENT AND RESULTS

For the experiment the different distance threshold ϵ used for clustering are varied among the values 10, 15 and $20\,\mu\mathrm{V}$. A neighbourhood of $L = 100\,\mathrm{ms}$, i.e. segment of $200\,\mathrm{ms}$ which incorporates the QRS complex is used in the clustering process.

For the results table 2 shows the number of records within each axis deviation category. A, B, C are isoelectric adjusted with $\epsilon = 10, 15$, and $20\,\mu\mathrm{V}$ respectively, and D is unadjusted. Table 3 shows the intersection, that is the number of records within the same axis category that are shared, with D - V_{rs}. Table 4 shows the row deviation. An example of ECG with signal averaging and isoelectric correction is shown in figure 1. Figure 2, 3, and 4 show zoomed PQ-segment of lead I, aVR and -aVR respectively.

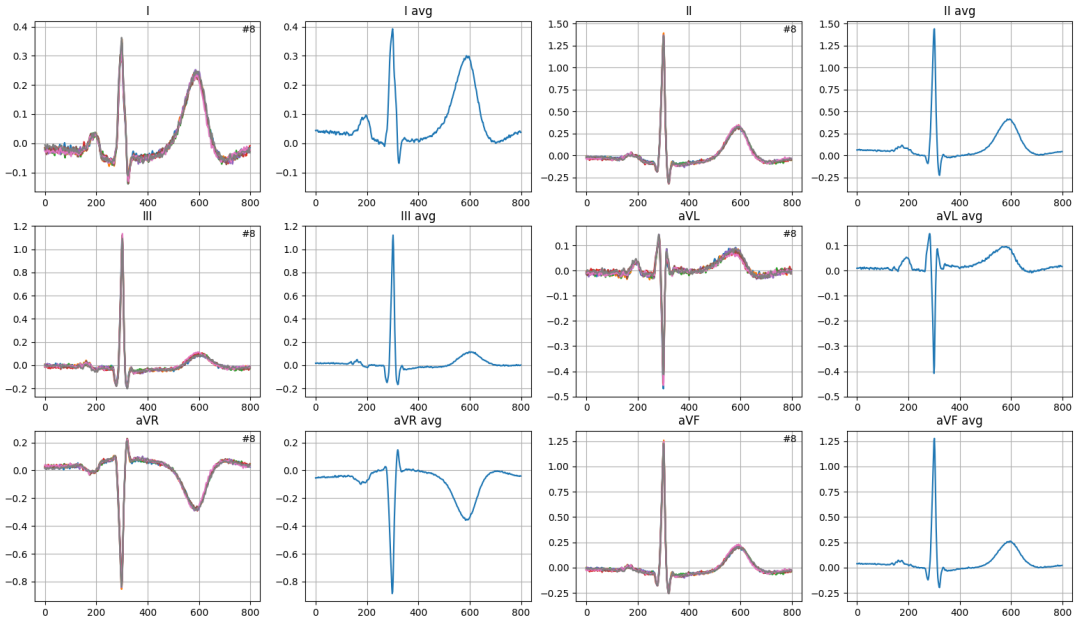

Fig. 1. Signal averaging with 8 overlapped signal segments and corresponding averaged template. The templates have been isoelectric adjusted, PQ-segment forced to 0 V. Unit of measurements are mV and ms. $\epsilon = 10$.

Table 1. Axis deviation criteria range [12].

Mark left axis deviation	$[-90\,^\circ, -45\,^\circ)$
Moderated left axis deviation	$[-45\,^\circ, -30\,^\circ)$
Normal	$[-30\,^\circ, 90\,^\circ]$
Mark right axis deviation	$(90\,^\circ, 120\,^\circ]$
Moderated right axis deviation	$(120\,^\circ, 180\,^\circ]$
Undefined	else

Table 2. The number of records within each axis deviation category. A, B, C are isoelectric adjusted with $\epsilon = 10, 15$, and $20\,\mu$V respectively, and D is unadjusted.

	A		B	
	Varea	Vrs	Varea	Vrs
Mark left axis deviation	53	22	53	22
Moderated left axis deviation	61	39	58	38
Normal	2815	2905	2822	2906
Moderated right axis deviation	74	44	70	44
Mark right axis deviation	3	1	3	1
Undefined	6	1	6	1
	C		D	
	Varea	Vrs	Varea	Vrs
Mark left axis deviation	53	22	252	42
Moderated left axis deviation	58	39	123	51
Normal	2818	2906	2100	2830
Moderated right axis deviation	75	43	348	82
Mark right axis deviation	3	1	91	4
Undefined	5	1	98	3

4. DISCUSSION AND CONCLUSION

Figure 1 shows that the proposed method is able to estimate and correct the isoelectric level. It can be seen from the figure that the PQ-segment is forced to 0 V. By the definition of a wave [5] it can be seen in figure 2 that lead I does not have a Q wave. Figure 2 also illustrates a dilemma. The PQ-segment is tilted, where the difference of the amplitude at P-offset and QRS-onset is approximately $20\,\mu$V. Depending on the measurements of reference points the amplitude

Table 3. The number of records within each axis category that are the same with D - Vrs of table 2. (Intersection)

	A		B	
	Varea	Vrs	Varea	Vrs
Mark left axis deviation	30	20	32	20
Moderated left axis deviation	28	24	27	23
Normal	2768	2829	2773	2829
Moderated right axis deviation	49	39	49	39
Mark right axis deviation	1	1	1	1
Undefined	1	1	1	1
	C		D	
	Varea	Vrs	Varea	Vrs
Mark left axis deviation	31	20	33	42
Moderated left axis deviation	27	24	7	51
Normal	2770	2830	2099	2830
Moderated right axis deviation	50	39	45	82
Mark right axis deviation	1	1	4	4
Undefined	1	1	3	3

measurements may differ by $\pm 20\,\mu$V within this lead, which is an acceptable error [5].

Figure 3 and 4 depicts the effect of clustering from lowest to highest amplitude and the reverse. The order of amplitudes either ascending or descending give different results. However, it appears for $\epsilon = 10\,\mu$V that this does not affect the estimated isoelectric bias much. This, of course, is just for this particular ECG and may be different for other recordings. To make it more consistent then perhaps -aVR should be used instead of aVR.

Another interesting point to notice is that the peak from 260 ms to 280 ms does not satisfy the criteria to be a wave according to [5]. The local QRS-onset appear to be at 260 ms, but since the peak is not valid the local QRS-onset is at peak's maximum (aVR). This is not ideal. A wave segmentation (delineation) algorithm might try to enforce an r peak (aVR) since there is a positive and a negative slope with a clear turning point. This would shift the QRS-onset and the reference point, and might induce a wave labeling error. However, if it is accepted that there is no r peak and that the QRS-onset is at the

Table 4. Row deviation with all combination of lead pairs. A, B, C are isoelectric adjusted with $\epsilon = 10, 15, 20\,\mu V$ respectively, and D is unadjusted. (Degree, $^\circ$)

		A		B	
		Varea	Vrs	Varea	Vrs
I	II	5.23	6.97	5.30	7.02
I	III	6.01	6.44	5.40	6.48
I	aVF	3.84	4.87	3.96	4.88
I	aVL	5.97	10.41	10.39	10.38
I	aVR	9.16	10.70	6.59	10.75
II	III	5.42	5.22	4.80	5.26
II	aVF	7.88	7.30	6.27	7.11
II	aVL	3.84	5.01	3.47	5.02
II	aVR	7.10	8.74	7.31	8.76
III	aVF	7.05	9.12	5.89	9.13
III	aVL	6.62	10.57	9.46	10.74
III	aVR	6.76	4.99	4.86	5.02
aVL	aVF	3.81	5.92	3.62	5.94
aVL	aVR	3.98	8.55	4.14	8.57
aVR	aVF	4.37	5.83	4.62	5.78
	mean	5.80	7.38	5.74	7.39
	std	1.65	2.15	2.02	2.16
		C		D	
		Varea	Vrs	Varea	Vrs
I	II	6.71	6.98	7.04	11.18
I	III	3.76	6.46	7.12	10.19
I	aVF	3.68	4.88	4.23	8.20
I	aVL	10.39	10.33	15.35	14.86
I	aVR	10.14	10.87	9.76	13.19
II	III	5.65	5.23	4.59	8.34
II	aVF	6.60	7.23	5.80	10.18
II	aVL	6.34	5.03	7.08	7.53
II	aVR	8.53	8.91	10.23	11.74
III	aVF	6.24	9.13	5.85	13.86
III	aVL	5.04	10.83	9.12	15.62
III	aVR	5.44	5.01	7.18	8.22
aVL	aVF	3.63	5.85	4.56	9.66
aVL	aVR	6.07	8.56	11.43	10.52
aVR	aVF	4.97	5.78	4.56	8.92
	mean	6.21	7.41	7.59	10.81
	std	2.10	2.20	3.10	2.56

peak's maximum then the proposed clustering algorithm does set the reference point approximately at the middle of the PQ-segment.

For a more quantitative assessment of the effect of isoelectric adjustment through MEA calculation can be seen in table 4. A quick glance shows that the mean and standard deviation of the row deviation are less for A, B and C compared to D, where D is without the isoelectric level correction. B ($\epsilon = 15\,\mu V$) has the smallest mean with $5.74\,^\circ$, but A ($\epsilon = 10\,\mu V$) provides the smallest standard deviation with $1.65\,^\circ$. Smallest mean and standard deviation are achieved with the net potential V_{area}. A small standard deviation of the row deviation is perhaps preferable since it suggest that the isoelectric adjustment is consistent throughout the lead pairs. Though, a higher ϵ such as in B and C ($\epsilon = 20\,\mu V$), would be more robust to noise.

Table 2 shows that for isoelectric adjusted (A, B, C) data the number of records within each axis deviation category appear to be consistent within their respective net potential definition. Isoelectric unadjusted data D - V_{area} has a great number in the undefined category. There are approximately 700 records which are classified differently in the normal category between D - V_{area} and D - V_{rs}, which can be seen in table 3. This is significantly more compared to the isoelectric adjusted data. From table 3 it appears that the results from V_{rs} for isoelectric unadjusted data are relatively close to isoelectric adjusted results. Which suggest that the net potential V_{area} is more susceptible to isoelectric adjustment, while V_{rs} is less susceptible to isoelectric adjustment. This might be because there are less number of samples used in the calculation of V_{rs}, and the fact that the area under the curve depends on isoelectric level of the signal. Comparison and validation with other methods is further works.

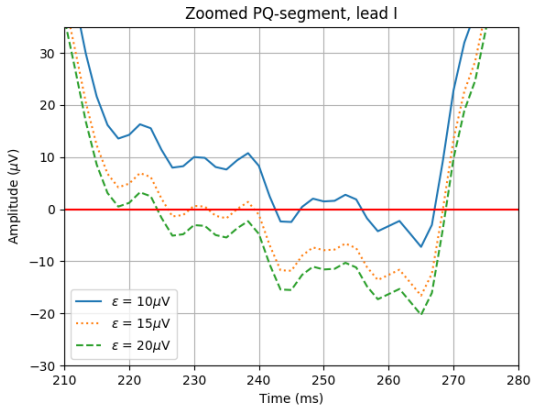

Fig. 2. Zoomed isoelectric adjusted PQ-segment of lead I of the same ECG as in figure 1.

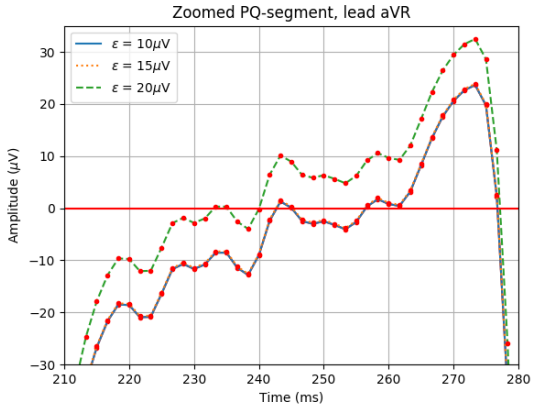

Fig. 3. Zoomed isoelectric adjusted PQ-segment of lead aVR of the same ECG as in figure 1. Red dots are samples of the signal.

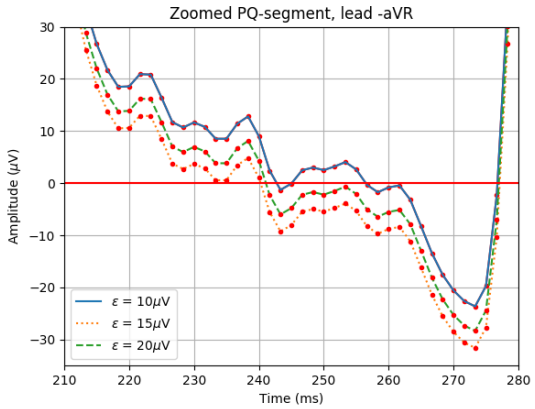

Fig. 4. Zoomed isoelectric adjusted PQ-segment of lead -aVR of the same ECG as in figure 1. Red dots are samples of the signal.

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