Limitations on the Re-Use of Patient Specific Coefficients for 12-Lead ECG Reconstruction

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Abstract

Patient specific coefficients for reconstructing missing precordial leads (patient-specific single-use or PSS) show good performance but require a 12-lead ECG to start monitoring. A more convenient approach is either the use of population based coefficients (POP) or patient specific coefficients from an old 12-lead ECG (patient-specific multi-use or PSM). We used a data set of 1493 resting 12-lead ECGs from 224 patients. Waveform comparisons were made between recorded 12-lead and reconstructed cases using RMS difference. Three cases were compared, PSS, PSM and POP. Median RMS reconstruction error in the ST-T region was 16, 46 and 40μV for lead configuration V1/V4 in the PSS, PSM and POP cases respectively. For the V2/V5 configuration, median ST-T RMS error was 8, 40 and 41μV. The RMS error for the PSS case was lower and significantly better by paired T-test. The difference between the two more convenient use-models, PSM and POP, was not significant. Population based coefficients are preferred over patient-specific coefficients if the single-use use-model cannot be followed.

1. Introduction

Retaining a small number of electrodes as with typical 5-wire arrhythmia monitoring but getting the benefit of gold standard 12-lead ECG morphology coverage is an appealing proposition for caregivers and patients alike. The caregiver has less trouble with many electrodes falling off or getting in the way of treatment while the patient's experience is improved by reducing the tangle of tubes and wires.

12-lead ECG reconstruction with reduced lead sets has been pursued for monitoring in several ways, but an appealing method to get good performance with familiar electrode placement is by derivation of patient specific coefficients from a standard 12-lead ECG. The patient specific coefficients can be used to reconstruct missing precordial leads from a subset of leads from that point forward while monitoring. Several authors have reported good results using this configuration [1-3]. The results compare favourably to using population based coefficients.

The main problem with using patient specific coefficients in this manner is the requirement for the initial high quality 12-lead ECG to be used for coefficient derivation. For patient-specific coefficient derivation, all leads are required and artefact will affect the accurate of patient specific coefficient calculation. It would be preferable to use a previous 12-lead if available, from the previous day or even the previous year.

In this study, we compare three use-models using 12-lead ECG. First, the ideal case where an ECG is used to derive the closest reconstruction possible, reconstruction of itself or single-use patient-specific coefficients (PSS). Second, a previous ECG is used to generate patient specific coefficients for later reconstruction, or patient-specific multi-use (PSM). Finally, population based coefficients (POP) are used for reconstruction of leads from a subset of precordial leads.

2. Methods

The resting 12-lead ECGs (10 second recording, 500Hz sample rate, 5μV amplitude resolution) were taken from a larger sequential set, selected for multiple ECGs per patient for a total of 224 patients and 1493 ECG records. The average patient age was 63 yrs, 61+/-15 yrs for males (n=147) and 63 +/- 15 yrs for females (n=77). Serial comparison of each ECG to the previous ECG was performed by a cardiologist to determine if the ECG represented a significant rhythm or contour change.

Waveform reconstruction error was calculated based on average beats. The Philips 12-lead algorithm was used to determine QRS onset, T offset and the set of beats to use in the averaged representative beat across the 10 second records. All further processing was performed using custom MatLab programs. The 10 second signals were highpass filtered with a 0.67Hz zero-phase filter to remove baseline wander without ST segment distortion. Representative beats were generated for the recorded 12-lead and reconstructed records from the same fiducial measurements. Waveform error was calculated by the

root-mean-squared (RMS) difference for the entire QRST region, just the QRS portion and also the ST-T wave portion of the complex. QRS offsets used to separate the QRS and ST-T portions of the complex were calculated by the line-segment method according to the method already presented [4].

Two variations of reconstructed lead combinations are presented here. In the first set, precordial leads V1 and V4 are used, along with the limb leads, to reconstruct missing leads V2, V3, V5 and V6. In the second case, limb leads and chest leads V2 and V5 were used to reconstruct missing leads V1, V3, V4 and V6. Each reconstructed lead is a linear combination of the input leads. Lead combinations V1/V4 and V2/V5 were selected from a larger set including V1/V6, V1/V5, V2/V6 by a combination of waveform error criteria and performance of a 12-lead algorithm using the reconstructed ECGs [5]. The V2/V5 lead set was also found to be the best 2 precordial lead combination by Nelwan [3].

The population based reconstruction coefficients were generated in the same manner as coefficients for the EASI transform using body surface ECG from the Dalhousie superset by regression analysis [6]. The patient specific coefficients calculated for this study were generated by robust linear regression using the QT interval of the average beat. ECGs with missing leads were excluded. Multi-use patient specific coefficients (PSM) were generated for each ECG from the immediately previous ECG in the same way the cardiologist reviewed current and previous ECGs. ECG #1 was the previous for ECG #2 and ECG #2 was the previous for ECG #3 and so on. The patient's first ECG was excluded from analysis since there were no multi-use patient coefficients for that subset of ECG records. The total number of ECGs in the analysis set was 1242 after excluding the patient's first ECG (n=224), and ECGs with paced rhythm, missing leads and poor technical quality (n=27).

RMS waveform reconstruction errors were described in terms of median for central tendency and interquartile range (IQR) for a measure of the spread of the data. Median and IQR are less sensitive to outliers than mean and standard deviation. Multiple one-tailed paired T-tests were used to find which type of reconstruction, PSS, PSM or POP offers lower RMS error. A 99% significance level was chosen for multiple T-test comparison as a compromise between no multi-test correction and the overly conservative Bonferroni correction [7]. The statistical software package S-plus was used for all statistical analyses.

3. Results

Tables 1 and 2 show the reconstruction error when using lead sets V1/V4 and V2/V5 respectively. For both lead configurations and both the QRS and STT regions, the RMS error for the PSS case is significantly lower than the RMS error for the PSM and POP cases by paired T-test (alpha = 99%). Since all median reconstruction errors are lower for the V2/V5 lead combination compared to the V1/V4 lead combination, we will only consider the V2/V5 lead combination.

Table 1. Comparison of RMS reconstruction error for the V1/V4 lead set between the PSS, PSM and POP cases showing a significant difference between PSS and the other two cases, PSM and POP.

Reconstruction Error (RMSμV)	**QRS region**		**ST-T region**	
	Median	IQR	Median	IQR
PSS	84	76	16	13
PSM	181	152	46	44
POP	191	149	48	40

Table 2. Comparison of RMS reconstruction error for the V2/V5 lead set between the PSS, PSM and POP cases showing a significant difference between PSS and the other two cases.

Reconstruction Error (RMSμV)	**QRS region**		**ST-T region**	
	Median	IQR	Median	IQR
PSS	61	60	8	7
PSM	152	138	40	39
POP	163	142	41	37

Table 3. Comparison of RMS reconstruction error for the V2/V5 lead set between the PSS, PSM and POP cases using patient-specific coefficients calculated from just the QRS region.

Reconstruction Error (RMSμV)	**QRS region**		**ST-T region**	
	Median	IQR	Median	IQR
PSS	31	29	43	41
PSM	147	141	56	56
POP	163	142	41	37

4. Discussion and conclusions

From Tables 1 and 2 it is clear that patient-specific single-use (PSS) coefficients outperform the patient-specific multi-use (PSM) and population (POP) based coefficients. There is a statistically significant difference in RMS error between the PSS and PSM cases. There is also a statistically significant difference in RMS error between the PSS and POP cases. When the patient specific coefficients are calculated over just the QRS region as shown in Table 3 instead of the entire QT interval as in Table 2, there is a wide difference between the PSS case and the PSM case in the QRS region but not the STT region. Using the entire QT interval for coefficient derivation results in a trade-off, lower error in the STT region and slightly higher error in the QRS region. Since we are concentrating on ST monitoring, lower ST error is more important and therefore coefficients calculated over the entire QT interval are preferred.

Several authors comparing patient specific and population based reconstruction coefficients have come to the same conclusion. Patient specific (single-use) coefficients outperform population based coefficients in terms of reconstruction error. Horacek [8] followed the PSS method as did Nelwan [2]. Horacek used waveform error criteria to rank various lead combinations to arrive at the best near-equivalent choices. Nelwan used a combination of waveform error and ST segment estimation error to arrive at the conclusion that patient specific coefficients (single-use) outperform populaton based coefficients.

The wide difference between reconstruction error for the PSS and POP cases is not surprising. We expect the error to be much lower for patient-specific coefficients. The surprising result is the similar error between the POP and PSM cases and the large difference between the two patient-specific cases. The following are possible causes of the difference between the single-use and multi-use patient-specific results: (1) variation in electrode placement between the previous and reconstructed ECGs, (2) change in rhythm, (3) change in QRS or ST-T morphology, and (4) ECG changes over time. We have measures for the potential causes above except for variation in electrode placement.

A linear regression model was used to estimate the effect of the hypothesized error sources. The PSM reconstruction error was considered to the be sum of (1) linear model fit error represented by the PSS error, i.e. the error in estimating a lead as a linear combination of other leads, (2) error due to a change in rhythm, (3) error due to a change in ECG contour, (4) error due to the elapsed time between the ECG used for coefficient calculation and the ECG reconstructed using those coefficients and (5) error due to variation in electrode placement. The residual error of the linear regression model for PSM will contain the error due to variation in electrode placement since we had no measure of this quantity.

The results of the linear regression fit of the PSM RMS error are shown in Table 4. Since we are concentrating on the ST monitoring application, we model only the error in the ST-T region in Table 4. The dependent variable is PSM RMS error and the independent variables are given in the table. The columns show, from left to right, the regression coefficient, p-value for that coefficient, the median value of the variable and the effect using the median value multiplied by the linear regression coefficient. For the model of the PSM RMS error in the STT region, the effect from the intercept, 33uV, is much stronger than the next significant variable, contour change, at 10uV. Linear model fit shows less of an effect and there remaining variables, rhythm change and elapsed time between previous and reconstructed ECG are not statistically significant contributors. Since the regression model explains 76% of the variance, a fairly high value, we can conclude that the independent variables have little effect on the PSM RMS error in the STT region. The error making up the intercept of the linear regression is the largest contribution to the PSM error.

Table 4. Linear regression model of RMS error in the PSM case including regression coefficients, statistical significance and median effect. The dependent variable is PSM RMS error in the ST-T region. Independent variables are shown in the table. The linear regression model accounts for 76% of the variation in the data (R^2=0.76).

Independent Variable (input)	Coef	p-value	Median input	Median effect
Intercept		0.00	NA	33μV
Contour change	10.4	0.005	1	10μV
Linear model fit	0.87	0.00	8μV	7μV
Rhythm change	7.4	0.05	1	NS
Elapsed time	0.02	0.07	1day	NS

Table 5. Summary statistics for the independent variables used to model the PSM RMS error.

Independent Variable	1st quartile	Mean	Median	3rd quartile
Rhythm change (T/F)	0 (false)	0.36	0 (false)	1 (true)
Contour change (T/F)	0 (false)	0.45	0 (false)	1 (true)
Elapsed time (days)	0.36	39	1.0	3.2

Table 5 shows the summary statistics for the independent or input variables for the linear regression model of the PSM RMS reconstruction error. Both rhythm change and contour change are logical variables translated to 0 and 1 for numerical purposes. Both logical values are false more often than true. Elapsed time between the previous ECG and the reconstructed ECG is in units of days. It is clear that the distribution of the elapsed time input is far from normal. The mean is 39 days while the median is 1 day indicating that there are many small values and few larger values but the large values have a significant impact on the mean.

Schijvenaars et. al. presented a review paper on intra-individual variability which may help put these results in context [9]. The review paper discussed variability associated with electrode placement, and time between ECGs, both of which apply here. Several studies found changes in precordial lead measurements due to variation in electrode position. The good linear regression fit for PSM error in the STT region presented above in Table 4 allows us to rule out time between ECGs as a major source of the difference between the PSS and PSM cases. We also note that the effect due to rhythm and contour change is small. Variation in electrode placement remains as the likely explanation for the largest share of the PSM RMS error. This conclusion is supported by the work of Nelwan et.al. [2]. They presented results similar to the "PSS" case in terms of electrode placement but also close to the "PSM" use-model in terms of elapsed time between calculating coefficients and using the coefficients as they compared waveforms over 24 hours of monitoring. Although the time scale is different, 24 hrs of monitoring versus a median of 24 hrs between 12-lead ECGs, the good results over 24 hours of monitoring lead to the same conclusion – low error over time means that electrode placement is the likely major cause of reconstruction error in the "PSM" use-model presented here. Because the reconstruction error remained low over 24 hours of monitoring, elapsed time between ECG snapshots can be ruled at as a major contributor to the reconstruction error in the "PSM" scenario, just variation in electrode placement remains as the likely source of the difference.

In conclusion, patient specific coefficients improve reconstruction as long as the electrodes are not moved between the ECG used to generate coefficients and the ECG for clinical use when the coefficients are applied. If the electrodes are reapplied, reconstruction error is equivalent between POP based coefficients and patient specific coefficients.

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