Optimal Placement of Dual Chest Leads for Deriving 12-Lead/18-Lead Electrocardiograms and Vectorcardiograms

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Abstract

Our aim was to develop and evaluate transformations for deriving standard 12-lead ECG, 18-lead ECG (with added V7 – V9, V3R – V5R), and Frank VCG from lead sets using 3 limb electrodes at Mason-Likar sites and 2 electrodes at V1 – V6 sites. The study population consisted of 290 normal subjects and 602 patients with previous myocardial infarction or ventricular tachycardia. Required ECG data were extracted from 120-lead recordings and transformation coefficients were derived by regression analysis. The ability of reduced lead sets to derive complete ones was assessed by 2 measures of fit: similarity coefficient and relative error. Results show that 6 out of 15 possible pairs of Mason-Likar chest leads (namely V1 & V4, V1 & V3, V2 & V5, V2 & V4, V3 & V6, and V3 & V5), used together with Mason-Likar limb leads, are best suited for reconstructing the complete 12-lead ECG and 18-lead ECG, as well as the VCG. In conclusion, our study shows that judiciously chosen reduced lead sets can approximate conventional ECG/VCG very satisfactorily.

1. Introduction

Electrocardiographic monitoring in special care units allows non-invasive detection and documentation of cardiac ischemic and arrhythmic events in patients with acute coronary syndromes, and contributes significantly to the reduction of mortality in these patients [1,2]. Although current bedside monitors allow continuous monitoring of the 12-lead electrocardiogram (ECG), it is not always practical to record all of the 12 leads. Several studies have assessed how well the complete 12-lead ECG can be reconstructed from various subsets of constituent leads [3-5]. In our previous study [6], we compared the abilities of various reduced lead sets to detect ST-segment changes associated with acute ischemia. The goal of the present study is to investigate the ability of 15 reduced lead sets that use two precordial chest leads—in addition to Mason-Likar (M-L) limb leads—to predict ECG waveforms of 12-lead/18-lead sets and orthogonal leads.

2. Methods

2.1. Database

The required ECG data for this study (the standard 12-lead ECG with limb electrodes at wrists and ankles; 6 additional leads, V7 – V9 and V3R – V5R, of 18-lead ECG; M-L 18-lead ECG [7]; and 7 unipolar leads required for synthesis of Frank X, Y, Z leads [8]) were extracted from the Dalhousie University body-surface potential mapping database. We used a study population consisting of 892 individuals, who were classified into 5 groups; the main clinical characteristics of these groups are summarized in Table 1. The diagnosis of myocardial infarction (MI) was based on non-ECG evidence in the acute phase—which included prolonged, ischemic-type chest pain, and a peak creatine kinase enzyme level more than twice the upper limit of normal—and the presence of diagnostic 12-lead ECG changes. The patients in the group with a history of ventricular tachycardia (VT) presented with electrocardiographically documented sustained VT in the absence of a reversible cause, such as electrolyte imbalance or proarrhythmic drug effect. All subjects were informed of the study procedures, in accordance with the ethical guidelines approved by the institutional Ethics Committee.

Table 1. Clinical characteristics of study population consisting of five diagnostic groups.

	N	M/F	Age, y	QRSd	HR
G1	290	163/127	36±12	99±10	62±10
G2	36	26/10	61±11	106±17	60±10
G3	282	235/47	58±11	105±15	65±13
G4	179	155/24	62±10	122±25	72±14
G5	105	79/26	55±14	118±26	71±14

G1, normal subjects; G2, patients (pts) with non-Q MI & no VT; G3, pts with Q-wave MI & no VT; G4, pts with MI & VT; G5, pts with VT & no MI; M/F, male/female; QRSd, QRS duration (ms); HR, heart rate (beats per minute); values with ±, mean ± standard deviation.

2.2. ECG acquisition and processing

The original ECG data were recorded simultaneously from 120 leads for each patient; the lead array had 3 limb leads at wrists and ankles and 117 unipolar chest leads (76 placed anteriorly and 41 posteriorly) [9]. Recordings were made for 15 consecutive seconds, while the subjects were supine. The acquisition system and the method of ECG signal averaging have been previously described [9]. Briefly, analog ECGs were amplified, filtered (bandpass from 0.025 to 125 Hz), multiplexed, and digitized at a rate of 500 12-bit samples per second per channel (with 2.5 μV resolution for the least-significant bit). Subsequent data processing was performed off line on an RS/6000 computer (IBM Corp, Armonk, NY). From the 15-second recordings, individual complexes were identified and sorted into families based on QRS morphology. The beats in the largest family were averaged and the baseline was corrected to yield a single representative complex for each lead. The onsets and offsets of ECG waves were determined by computer algorithms and verified manually on a screen. The averaged complexes were plotted in a format that resembled the layout of the electrodes on the chest, and these plots were edited to eliminate leads with artifacts. A three-dimensional interpolation was performed to replace rejected leads and produce ECGs for 352 locations on the torso [9]. From these data, we extracted ECG waveforms of the required leads.

2.3. Transformation coefficients

Reduced lead sets of interest in this study used three limb electrodes at M-L sites [7] combined with 2 chest electrodes at precordial sites V1 – V6; there are 15 such lead-set combinations, which can be recorded with 6-wire cable. For these reduced lead sets we derived coefficients for lead transformations by means of regression analysis [10]. The objective was to fit a regression model to the given dataset, in order to obtain a statistical estimate V' of the instantaneous voltage V at a given predicted lead by fitting the linear regression equation without intercept

$$V' = \sum_{i=1}^{k} \beta_i V_i$$

to the recorded voltages V_i in k predictor leads. The problem is to find the best-fitting coefficients β_i for predictor leads $i = 1, \ldots, k$. Our approach was to look for such estimates of β_i that minimized the error sum of squares over all available data samples of the QRST interval for all subjects of our study population. To perform a least-squares solution to the linear-regression problem, we used a general-purpose procedure for regression (PROC REG) from the SAS System [11]. The transformation coefficients that best fitted the available data were then applied as constants to the time-varying ECG signals of predictor leads to obtain the estimated time-varying ECG signals in desired predicted leads of the complete 12-lead/18-lead sets and of the VCG; for instance, for predictor leads II, III, V2, and V5, any desired lead can be derived by using appropriate coefficients in the equation of the type:

$$V'(t) = \beta_{\mathrm{II}} V_{\mathrm{II}}(t) + \beta_{\mathrm{III}} V_{\mathrm{III}}(t) + \beta_{\mathrm{V2}} V_{\mathrm{V2}}(t) + \beta_{\mathrm{V5}} V_{\mathrm{V5}}(t).$$

The transformations were then assessed and ranked by using quantitative measures for the goodness of fit.

2.4. Ranking of transformations

The ability of transformation coefficients obtained by regression analysis to derive desired leads from sets of predictor leads was assessed by 3 measures for goodness of fit. To define these measures, let us denote the recorded and estimated voltages in a given lead for a given subject at a sampled instant i as V_i and V_i', respectively. Using this notation, we define the relative error (*RE*) as a dimensionless ratio of rms error and signal energy

$$RE = \sqrt{\frac{\sum_{i=1}^{n} \left(V_i - V_i'\right)^2}{\sum_{i=1}^{n} V_i^2}}$$

and the similarity coefficient (*SC*) as a dimensionless ratio

$$SC = \frac{\sum_{i=1}^{n} V_i V_i'}{\sqrt{\sum_{i=1}^{n} \left(V_i\right)^2} \sqrt{\sum_{i=1}^{n} \left(V_i'\right)^2}}$$

where index i runs for each derived lead from 1 to n over all samples of the QRST complex for the entire study population. In addition to these two measures pertaining to all samples of the QRST interval, we used also a relative error measure *RE** defined for a single sample (J + 60 ms) of the ST segment.

3. Results

The ability of transformations to derive desired lead *sets* from each of 15 predictor lead sets was assessed by using *mean* values of *SC*, *RE*, and *RE** for all constituent leads of the derived set. Performance ranking of predictor lead sets was based on the first measure (mean *SC*); the second measure (mean *RE*) produced virtually identical ranking; the third measure (mean *RE**) produced ranking that did not necessarily follow that based on mean *SC*, but it was consistent with it for the top-ranked predictor lead sets. Table 2a summarizes the ability of 8 top-ranked reduced lead sets to derive the standard 12-lead ECG, with limb electrodes attached properly at wrists and ankles. Table 2b is analogous to Table 2a; it shows how well top-ranked reduced lead sets can reconstitute the

complete M-L 12-lead ECG (i.e., to predict just 4 missing precordial chest leads). It can be noted that ranking of the first 6 reduced lead sets in Tables 2a and 2b is identical. Further inspection of these tables shows that the differences in measures of fit among all listed lead sets are small, which implies that there are several near-equivalent choices.

Table 2a. Ability of various lead sets using M-L limb leads and dual chest leads to derive conventional 12-lead ECG (with *bona fide* limb leads).

Rank	Chest leads	*SC* (%)	*RE* (%)	*RE** (%)
1	**V2 & V4**	96.91	25.53	38.19
2	**V3 & V5**	95.89	26.22	38.56
3	**V2 & V5**	95.86	26.52	38.26
4	V3 & V4	95.82	26.49	39.52
5	**V1 & V4**	95.72	27.05	39.42
6	V2 & V3	95.56	27.27	40.87
7	**V1 & V3**	95.41	27.76	40.92
8	**V3 & V6**	95.39	27.87	39.93

SC, similarity coefficient over QRST; *RE*, relative error over QRST; *RE**, relative error at J + 60 ms; *SC*, *RE*, *RE** are mean values over all predicted leads.

Table 2b. Ability of various lead sets using M-L limb leads and dual chest leads to reconstitute the complete M-L 12-lead ECG.

Rank	Chest leads	*SC* (%)	*RE* (%)	*RE** (%)
1	**V2 & V4**	98.38	9.93	11.87
2	**V3 & V5**	98.21	10.54	11.24
3	**V2 & V5**	98.20	10.80	11.40
4	V3 & V4	98.14	10.77	12.73
5	**V1 & V4**	97.78	11.87	13.20
6	V2 & V3	97.73	11.96	14.54
7	**V3 & V6**	97.66	12.19	13.06
8	**V1 & V3**	97.33	12.85	14.63

Table 3a lists 8 top-ranked reduced lead sets with the best ability to derive the 18-lead ECG with limb electrodes attached at wrists and ankles, and analogous Table 3b shows the ability of top-ranked subsets of M-L 12-lead ECG to reconstitute the complete M-L 18-lead ECG (i.e., to predict 4 missing precordial leads, 3 right-sided leads and 3 posterior leads). By comparing Table 3b with 3a, ascendance of V3 & V6 in ranking can be noted, but since differences in measures of fit among all listed reduced lead sets are small, this is not a significant change (considering that both tables contain the same 8 pairs of chest leads, out of possible 15).

Table 3a. Ability of various lead sets using M-L limb leads and dual chest leads to derive conventional 18-lead ECG (with *bona fide* limb leads).

Rank	Chest leads	*SC* (%)	*RE* (%)	*RE** (%)
1	**V1 & V4**	93.82	31.93	42.78
2	**V1 & V3**	93.71	32.26	44.09
3	V1 & V5	93.38	32.94	43.17
4	V1 & V6	93.31	33.10	44.87
5	**V3 & V6**	93.28	33.53	43.62
6	**V2 & V4**	93.19	33.12	43.88
7	**V3 & V5**	93.02	33.63	43.88
8	**V2 & V5**	92.95	33.91	43.68

Table 3b. Ability of various lead sets using M-L limb leads and dual chest leads to derive the M-L 12-lead ECG plus 6 additional right-sided and posterior leads.

Rank	Chest leads	*SC* (%)	*RE* (%)	*RE** (%)
1	**V3 & V6**	94.75	23.17	25.94
2	**V1 & V4**	94.55	22.71	26.23
3	**V1 & V3**	94.37	23.20	27.91
4	**V2 & V4**	94.34	23.14	26.85
5	V1 & V6	94.24	23.61	28.06
6	**V3 & V5**	94.24	23.54	26.31
7	**V2 & V5**	94.16	23.82	26.28
8	V1 & V5	92.13	23.62	26.24

Table 4 shows reduced lead sets that can best derive 3 orthogonal leads of the Frank vectorcardiographic lead system [8]; it contains the same group of reduced lead sets as Tables 3a and 3b. Comparison of ranking tables (Tables 2a, 2b, 3a, 3b, and 4) reveals that reduced lead sets with 6 pairs of chest leads (highlighted in bold face) appear in all tables. For four of these reduced lead sets lead-by-lead statistics showing how well individual leads of the conventional 18-lead ECG and of the VCG can be derived are in Table 5.

Table 4. Ability of various lead sets using M-L limb leads and dual chest leads to derive Frank orthogonal X, Y, Z leads.

Rank	Chest leads	*SC* (%)	*RE* (%)	*RE** (%)
1	**V3 & V6**	96.31	26.07	35.50
2	**V1 & V3**	96.11	27.25	37.92
3	**V1 & V4**	96.07	27.70	37.56
4	**V3 & V5**	96.06	27.05	36.08
5	V1 & V5	95.80	27.76	37.44
6	**V2 & V5**	95.70	28.12	36.60
7	**V2 & V4**	95.70	28.93	38.29
8	V1 & V6	95.62	28.52	38.67

Table 5. Similarity coefficients (%) of 4 predictor lead sets using M-L limb leads and dual chest leads to derive the 18-lead ECG (with *bona fide* limb leads) and VCG.

	V1 & V4	V1 & V3	V2 & V5	V2 & V4
aVL	92.88	92.99	92.71	92.65
I	95.78	95.81	95.93	95.77
aVR	97.94	97.91	97.96	97.90
II	97.54	97.53	97.26	97.32
aVF	95.54	95.59	95.03	95.17
III	93.20	93.30	92.68	92.78
V5R	91.54	91.45	87.45	87.87
V4R	93.99	93.86	87.50	87.96
V3R	97.42	97.38	89.56	89.78
V1	**99.60**	**99.60**	93.73	93.69
V2	92.68	95.98	**99.85**	**99.85**
V3	94.64	**99.78**	95.39	98.31
V4	**99.72**	92.83	93.86	**99.72**
V5	95.78	90.73	**99.61**	96.11
V6	93.34	92.92	96.33	93.81
V7	89.77	90.33	90.86	90.36
V8	85.90	86.63	86.43	86.55
V9	81.55	82.14	81.00	81.73
X	96.48	95.22	98.27	96.53
Y	95.36	95.36	94.85	94.91
Z	96.37	97.75	93.99	95.64

4. Discussion

In our previous study [6], we ranked various subsets of the M-L 12-lead ECG according to their ability to detect myocardial ischemia from indices derived from ST deviation in all constituent leads of a given lead set; i.e., we wanted to determine to what extent *diagnostic* information (measured as an area under the receiver operating characteristic curve) is retained in reduced lead sets compared to the complete 12-lead ECG. In the present study, we ranked all possible subsets of M-L 12-lead ECG with two chest leads according to their ability to derive *waveforms* of the desired leads, without any regard to the diagnostic information they might yield.

Our previous results [6] indicate that the 3-lead sets with the best ability to detect ischemia are III, V3, V6 and III, V3, V5, and that two 3-lead sets using lead V1 (III, V1, V4 and III, V1, V3) have nearly the same ischemia-detection ability. In the present study, we found that 6 out of 15 possible pairs of M-L chest leads (including V3 & V6, V3 & V5, V2 & V4, V2 & V5, V1 & V4, and V1 & V3), used together with M-L limb leads, are all almost equally capable of reconstructing the complete 12-lead/18-lead ECG, as well as the VCG. Thus several options are available for continuous monitoring with 6-wire cable: dual chest leads V3 & V6 or V3 & V5 can be chosen to achieve superior ischemia detection; alternatively, dual chest leads V1 & V4 or V1 & V3 can be used to achieve superior arrhythmia detection as well as ischemia detection. For each of these options, the standard 12-lead/18-lead ECG and Frank VCG can be derived with an excellent degree of fit.

Acknowledgements

Support for mapping studies at Dalhousie University was provided by the Heart & Stroke Foundation of Nova Scotia and by the Canadian Institutes of Health Research.

References

[1] Mirvis DM *et al.* Instrumentation and practice standards for electrocardiographic monitoring in special care units. Circulation 1989;79:464–71.

[2] Drew BJ, Krucoff MW. Multilead ST-segment monitoring in patients with acute coronary syndromes: A consensus statement for healthcare professionals. Am J Crit Care 1999;8:372–88.

[3] Nelwan SP, Kors JA, Meij SH. Minimal lead sets for reconstruction of 12-lead electrocardiograms. J Electrocardiol 2000;33(Suppl):163–6.

[4] Drew BJ, Pelter MM, Brodnick DE, Yadav AV, Dempel D, Adams MG. Comparison of a new reduced lead set ECG with the standard ECG for diagnosing cardiac arrhythmias and myocardial ischemia. J Electrocardiol 2002;35(Suppl): 13–21.

[5] Nelwan SP, Kors JA, Meij SH, van Bemmel JH, Simoons ML. Reconstruction of the 12-lead electrocardiogram from reduced lead sets. J Electrocardiol 2004;37:11–8.

[6] Wang JY, Warren JW, Horáček BM. Sensitivity-specificity tradeoff for different alarm strategies in continuous 12-lead ST-segment monitoring. Computers in Cardiology 2004; 31:721–4.

[7] Mason RE, Likar I. A new system of multiple-lead exercise electrocardiography. Am Heart J 1966;71:196–205.

[8] Frank E. An accurate, clinically practical system for spatial vectorcardiography. Circulation 1956;13:737–49.

[9] Horáček BM, Warren JW, Penney CJ, MacLeod RS, Title LM, Gardner MJ, Feldman CL. Optimal electrocardiographic leads for detecting acute myocardial ischemia. J Electrocardiol 2001;34(Suppl):97–111.

[10] Kleinbaum DG, Kupper LL, Muller KE. Applied Regression Analysis and Other Multivariable Methods (Edition 2). Duxbury Press, Belmont, CA, 1988.

[11] SAS User's Guide: Statistics. SAS Institute Inc, Cary, NC, 1982.

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