Use of Dual Chest Leads for Deriving Complete 12-Lead/18-Lead Electrocardiograms and Vectorcardiograms in Infants

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Abstract

We developed infant-specific transformations of ECG leads and compared their performance with that achieved by transformations derived for adults. In particular, we studied the ability of 15 reduced lead sets consisting of Mason-Likar (M-L) limb leads and 2 precordial leads to predict the complete set of M-L 12 leads, plus right-sided, posterior, and orthogonal leads. The study population consisted of 82 infants aged 6 to 365 days, for whom 120-lead ECG data were available. Lead transformations were derived by regression analysis and the ability of reduced lead sets to predict desired leads was assessed by 3 measures of fit. The results show that, with infant-specific transformations, 12 pairs of precordial leads have almost the same predictive ability. In comparison of adult vs. infant transformations the former fared well for the right-sided, precordial, and orthogonal leads, but failed for the posterior leads; the latter performed well for all the leads and thus they are preferable.

1. Introduction

The pediatric electrocardiograms (ECGs) have to be interpreted—especially during the first year of life—with due regard to the age-specific changes associated with the anatomic/physiologic development of the heart [1]. The ECG is usually obtained only in children with symptoms; those with episodic symptoms (palpitations, chest discomfort, syncope) and with suspected arrhythmias require ECG monitoring [2,3]. For practical reasons, monitoring can only be performed with a limited number of leads. In our previous study [4], we investigated in *adults* the ability of reduced lead sets with only 2 precordial leads—in addition to Mason-Likar (M-L) limb leads—to predict ECGs of 12-lead/18-lead sets as well as orthogonal VCG leads. The aim of the present study is to assess: (1) whether the transformation coefficients that were derived for adults are applicable in infants, and (2) how much better can infant-specific coefficients perform compared to coefficients derived for adults.

2. Methods

2.1. ECG data

The required ECG data (the 12-lead ECG with "limb" electrodes at M-L sites [5]; right-sided leads V3R–V5R and posterior leads V7–V9 of 18-lead ECG; and 7 unipolar leads for synthesizing Frank's orthogonal X, Y, Z leads [6]) were extracted from the Dalhousie University body-surface potential mapping database. Study population consisted of 82 infants in 2 groups: normal infants (G1), and infants at risk of life-threatening events (G2), which were defined as in [7]. Figure 1 shows the age- and sex-distribution of this infant population, and the electrocardiographic characteristics of the group are shown in Table 1. Parents/guardians of all infants were informed of the study procedures, in accordance with the guidelines approved by the institutional Ethics Committee.

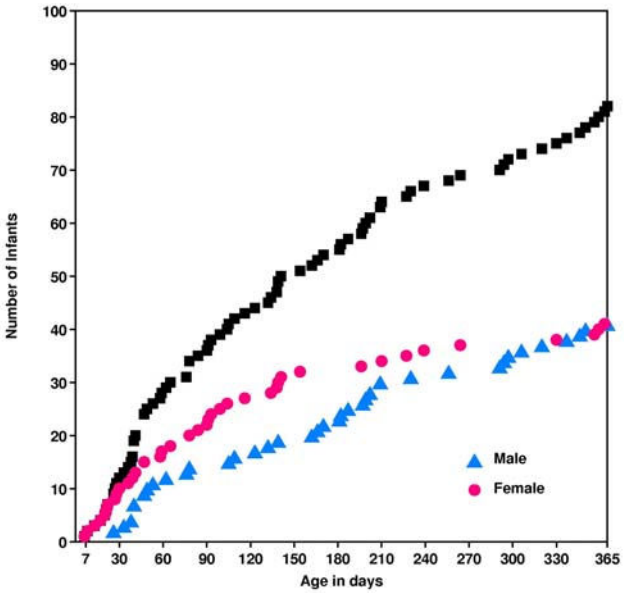

Figure 1. Cumulative distribution of age in days for 82 infants included in this study. Squares, all subjects; triangles, males; circles, females.

Table 1. Clinical characteristics of study population consisting of 2 diagnostic groups

	G	G1	G2
N	82	63	19
M/F	41/41	33/30	8/11
Age, days	139 ± 108	154 ± 110	90 ± 84
QRSd, ms	70 ± 9	70 ± 9	67 ± 7
HR, bpm	144 ± 17	146 ± 16	140 ± 21
QT, ms	282 ± 23	283 ± 23	281 ± 24
QTc, ms	435 ± 21	438 ± 21	426 ± 21

G, entire group; G1, normal infants; G2, infants at risk of life-threatening events; M/F, male/female; QRSd, QRS duration; HR, heart rate (beats per minute); QT, QT interval; QTc, corrected QT interval; values with ±, mean ± standard deviation.

2.2. ECG acquisition and processing

The ECG data were recorded simultaneously from 120 leads for each infant; using 3 limb leads at M-L sites [5] and 117 unipolar chest leads (76 placed anteriorly and 41 posteriorly) [8]. Recordings were made for 15 seconds; the acquisition system and the method of ECG signal averaging have been previously described [8]. Briefly, analog ECGs were amplified, filtered (bandpass from 0.025 to 125 Hz), multiplexed, and digitized at a rate of 500 10-bit samples per second per channel (with 10-μV resolution for the least-significant bit). Subsequent processing was done 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. Faulty leads were identified and a three-dimensional interpolation produced ECGs for 352 locations on the torso. From these data, the required leads were extracted.

2.3. Transformation coefficients

Reduced lead sets of interest in this study used 3 limb electrodes at M-L sites [5] combined with 2 chest electrodes at precordial sites V1–V6; there are 15 such combinations that can be recorded with 6-wire cable. For these reduced lead sets we derived coefficients for lead transformations by means of regression analysis [9]. The objective is 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 $i = 1, \ldots, k$. We looked 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 [10]. The transformation coefficients that best fitted the available data were then used to compute the lead to be predicted.

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. 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. The relative error (*RE*) can be then defined 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 2 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 lead transformations to derive desired lead sets from each of the 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 and the third measure (mean *RE**) produced ranking that was consistent with it for the top-ranked predictor lead sets.

Table 2. Ability of reduced lead sets consisting of 2 M-L limb leads and 2 precordial leads to predict the complete M-L 12-lead ECG by using infant-specific coefficients.

Rank	Chest leads	*SC* (%)	*RE* (%)	*RE** (%)
1	**V2 & V4**	98.69	8.93	14.14
2	**V1 & V3**	98.60	9.44	15.48
3	**V1 & V4**	98.59	9.49	16.63
4	**V2 & V5**	98.53	9.72	15.19
5	V2 & V3	98.45	9.92	14.92
6	V1 & V5	98.05	11.04	18.64
7	V2 & V6	98.03	11.13	17.77
8	V1 & V2	97.80	11.84	21.37
9	V3 & V4	97.77	11.32	14.99
10	V3 & V5	97.70	11.12	14.76
11	V3 & V6	97.52	11.69	15.46
12	V1 & V6	97.25	12.90	22.29
13	V4 & V5	94.75	16.06	25.55
14	V4 & V6	94.64	15.83	24.41
15	V5 & V6	91.22	20.70	32.67

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 2 shows the ability of all 15 reduced lead sets to derive the 12-lead ECG, with limb electrodes attached at M-L sites (i.e., to predict just 4 missing precordial chest leads) by means of infant-specific coefficients. The inspection of this table shows that differences in measures of fit among 12 out of 15 possible lead sets are very small.

Table 3. Ability of reduced lead sets consisting of 2 M-L limb leads and 2 precordial leads to predict the complete M-L 18-lead ECG (including 3 right-sided and 3 posterior leads) by using infant-specific coefficients.

Rank	Chest leads	*SC* (%)	*RE* (%)	*RE** (%)
1	**V1 & V4**	96.12	19.22	32.71
2	**V1 & V3**	96.09	19.26	31.76
3	**V2 & V4**	95.65	20.60	32.14
4	V1 & V5	95.65	20.41	34.87
5	V1 & V2	95.57	20.76	35.67
6	**V2 & V5**	95.52	21.15	33.44
7	V2 & V3	95.40	21.41	32.66
8	V2 & V6	95.17	22.14	33.71
9	V1 & V6	95.06	21.79	35.68
10	V3 & V4	94.50	23.24	33.13
11	V3 & V5	94.37	23.26	33.56
12	V3 & V6	94.26	23.66	32.58
13	V4 & V6	91.32	27.99	40.32
14	V4 & V5	91.29	28.34	42.61
15	V5 & V6	88.37	32.03	47.72

Table 3 shows the ability of the same 15 reduced lead sets to predict the M-L 18-lead ECG (i.e., to predict 4 precordial, 3 right-sided and 3 posterior leads).

Table 4. Ability of reduced lead sets consisting of 2 M-L limb leads and 2 precordial leads to predict Frank X, Y, Z leads by using infant-specific coefficients.

Rank	Chest leads	*SC* (%)	*RE* (%)	*RE** (%)
1	**V1 & V4**	96.91	24.54	47.14
2	**V1 & V3**	96.73	25.29	47.61
3	V1 & V5	96.71	24.49	49.49
4	**V2 & V5**	96.67	24.63	48.87
5	**V2 & V4**	96.50	25.94	48.65
6	V2 & V6	96.22	26.45	51.27
7	V2 & V3	96.06	27.67	50.51
8	V1 & V2	96.05	27.82	54.42
9	V1 & V6	95.89	27.42	53.76
10	V3 & V6	95.88	27.01	47.39
11	V3 & V5	95.84	27.14	47.52
12	V3 & V4	95.48	29.13	50.09
13	V4 & V6	92.97	32.78	61.26
14	V4 & V5	92.81	33.55	61.65
15	V5 & V6	89.50	37.92	72.99

Table 4 shows the ability of the same reduced lead sets to derive 3 orthogonal leads of the Frank VCG lead system [6]. Comparison of ranking tables (Tables 2–4) reveals that 12 reduced lead sets have near-equivalent prediction performance in all tables. For four of these reduced lead sets, lead-by-lead statistics are in Table 5.

Table 5. Similarity coefficients (%) measuring the ability of 4 predictor lead sets consisting of 2 M-L limb leads and 2 precordial leads to predict the complete M-L 18-lead ECG and VCG by using infant-specific coefficients.

	V1 & V4	**V1 & V3**	**V2 & V5**	**V2 & V4**
V5R	94.67	94.62	93.49	93.29
V4R	95.78	95.75	92.21	92.12
V3R	98.24	98.23	92.20	92.22
V1	100.00	100.00	93.90	93.96
V2	94.93	97.19	100.00	100.00
V3	96.52	100.00	95.66	98.44
V4	100.00	96.75	96.05	100.00
V5	97.35	95.24	100.00	97.43
V6	94.24	94.03	96.74	94.44
V7	86.12	86.28	86.17	86.72
V8	85.27	85.07	85.56	85.86
V9	86.98	86.41	87.40	87.19
X	97.60	96.81	98.84	97.62
Y	96.09	96.10	95.13	95.13
Z	97.05	97.27	96.03	96.75

Table 6. Similarity coefficients (%) measuring the ability of 4 predictor lead sets consisting of 2 M-L limb leads and 2 precordial leads to predict the complete M-L 18-lead ECG and VCG by using general coefficients derived from an adult population.

	V1 & V4	V1 & V3	V2 & V5	V2 & V4
V5R	94.11	94.18	92.14	92.02
V4R	95.53	95.65	89.93	89.64
V3R	98.12	98.16	87.59	87.23
V1	100.00	100.00	87.82	87.80
V2	93.73	96.94	100.00	100.00
V3	95.40	100.00	95.36	98.26
V4	100.00	95.58	95.29	100.00
V5	94.94	90.38	100.00	95.25
V6	87.64	86.55	95.13	88.82
V7	63.21	63.63	68.91	64.27
V8	53.44	53.82	56.63	52.91
V9	69.16	70.62	71.45	70.39
X	95.21	93.73	98.19	95.51
Y	94.96	94.91	93.37	93.39
Z	94.33	95.63	92.72	93.95

Tables 5 and 6 allow comparison of lead-by-lead performance, based on the SC, for predictions obtained by means of infant-specific coefficients (Table 5) and general coefficients (Table 6). Inspection of these tables reveals that the general transformations performed relatively well for the right-sided leads (SC > 87%), precordial leads (SC > 86%), and orthogonal leads (SC > 92%), but not for posterior leads (71% > SC > 52%).

4. Discussion

In our previous study [4], we ranked—in adult population—subsets of the M-L 12-lead ECG according to their ability to synthesize the standard 12-lead/18-lead ECG, with limb leads placed at M-L sites as well as at standard sites (wrists and ankles). The results indicated that 6 out of 15 possible pairs of chest leads (namely V1 & V3, V1 & V4, V2 & V4, V2 & V5, V3 & V5, and V3 & V6), used together with M-L limb leads, all have almost the same predictive ability.

The objective of the present study was to determine to what extent can the previously-derived general "adult coefficients" be used in infant population. The results show that in infant population there are as many as 12 out of 15 reduced lead sets with almost the same ability to predict the M-L 12-lead/18-lead ECG and VCG by means of infant-specific coefficients; lead pairs V1 & V4, V1 & V3, V2 & V4, and V2 & V5 show consistently the best predictive performance in terms of mean SC (95.5% < SC < 98.7%). Lead-by-lead comparison of SC (for the 4 top-ranked reduced lead sets) of general *vs*. infant-specific transformations shows that, as expected, the infant-specific transformations perform better than general ones in predicting desired leads. However, the general lead transformations derived for the adult population (that included postinfarction patients) seem to be robust enough to hold (at least for leads on the anterior chest) in the infant population of this study as well.

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