Reconstruction of Standard 12-Lead ECGs from 12-Lead ECGs Recorded with the Mason-Likar Electrode Configuration

S Man, AC Maan, E Kim, HHM Draisma,
MJ Schalij, EE van der Wall, CA Swenne

Leiden University Medical Center, Leiden, the Netherlands

Abstract

ECGs made with Mason-Likar electrode positions (ML-ECGs) show well-known differences from standard 12-lead ECGs (Std-ECGs). Until now, only 2x2 matrices to reconstruct the limb leads of standard ECGs from the limb leads of ML-ECGs have been published. We recorded Std-ECGs with 3 additional unipolar electrodes at the Mason-Likar extremity positions in 72 individuals and computed 2x2 and 8x8 conversion matrices by linear regression. Performances of these matrices were expressed as a percentage of the root-mean-squared differences (RMSD) between the reconstructed ECGs and the Std-ECGs, and by the differences in major ECG parameters. The overall performance of the Leiden 8x8 matrix was superior: it reduced RMSD till 62% (vs. 2x2-matrix reductions of 78-89%; P<0.001), had the smallest positive bias in the QRS frontal axis and in the maximal QRS- and T-wave amplitudes and "protected" against extreme errors in some individuals.

1. Introduction

Serial ECG comparison is valuable for the detection of emerging/evolving heart disease [1-3] and is typically retrospectively done. When some ECGs in a person were recorded by using the Mason-Likar modified extremity electrode positions (ML-ECGs) [4] as applied in monitoring conditions or during exercise tests, these ECGs cannot be compared with standard 12-lead ECGs (Std-ECGs) because of a number of well-known differences, like right axis deviation [5,6].

Matrix conversion is the usual technique to bridge incompatibilities due to alternate electrode configurations [7-11]. Attempts to reconstruct a standard 12-lead ECG from a Mason-Likar ECG have so far been restricted to the synthesis of the Einthoven extremity leads I and II from the Mason-Likar extremity leads I and II by a 2x2 conversion matrix [7,11]. Conversion coefficients were first published by Bartosik et al.[7]. Later, Nelwan published another set of conversion coefficients [11] and performance results [12].

Bartosik and Nelwan used the ECG recording approach first described by Pahlm et al. [13]. With this technique, the precordial leads V1–V6, that are also affected by the Mason-Likar electrode placement, cannot be reconstructed. Because of this limitation, and because of the strikingly large difference in coefficients $C_{1,1}$ (Bartosik: 1.479185, Nelwan: 0.9897), we undertook a new attempt to reconstruct standard ECGs from ML-ECGs. In our study, we recorded all 13 electrodes, thus facilitating full 12-lead 3D reconstruction and validation.

2. Methods

2.1. Study population

Patients visiting the outpatient clinic of the Cardiology Department of our hospital to perform an exercise test were invited to take part in this study. In addition, some medical students and personnel volunteered in this study.

ECGs were recorded in 72 subjects (48/24 male/female), aged 49±18 [19–86] years, BMI 25±4 [17–39] kg/m^2 and BSA 1.93±0.21 [1.49–2.37] m^2. Fourteen of these 72 subjects were students and personnel, 15 patients visited the outpatient clinic for screening purposes, 20 patients were known to have arrhythmias, 7 hypertension, 12 coronary heart disease and 4 heart failure.

2.2. ECG recording/generation

In each subject, a supine resting ECG was recorded with the "standard 15-lead electrode placement" modality of a CASE-8000 electrocardiograph (GE Medical Systems, Milwaukee, WI, USA). Normally, in this recording modality, three extra chest electrodes C3R, C4R and C7 are used to generate three extra precordial leads. For our study, these electrodes were placed at the Mason-Likar positions: C3R and C4R in the right and left infraclavicular fossae, respectively, medial to the border of the deltoid muscle and 2 cm below the lower borders of the clavicles, and C7 at the left iliac crest.

Afterwards, the recorded signals were exported to a

PC, and simultaneous Std-ECGs and ML-ECGs were calculated from the independent 11 leads I, II, V1–V6, V3R, V4R and V7 by using the method as described by Pahlm et al. [13]. All computing in this study was done in the MATLAB (The MathWorks, Natick, MA, USA; version R2006b) programming environment.

2.3. Conversion matrices and experiments

We generated 2x2 (leads I and II) and 8x8 (leads I-II, V1-V6) conversion matrices by linear regression (MATLAB function *glmfit*) thus minimizing the root-mean-squared-differences (RMSD) between the reconstructed standard ECG (ML2Std-ECG) and the originally recorded Std-ECG. Group conversion matrices were generated on the basis of a "group ECG" (the concatenated ECGs of all subjects in the group).

Several experiments with individual and group conversion matrices were done. Here, we discuss the following experiments:

1. *Leiden reconstruction.* Subjects were sorted on age and grouped into equally-sized learning (subjects 1&4, 5&8, *etc.*) and test (subjects 2&3, 6&7, *etc.*) sets; 2x2 and 8x8 group conversion matrices were computed on the basis of the learning set, and ML2Std-ECGs of all subjects in the test set were constructed by using these 2x2 and 8x8 "Leiden" matrices.
2. *Bartosik and Nelwan reconstruction:* construction of the ML2Std-ECG of all subjects in the same test set by using the 2x2 conversion matrices as published by Bartosik [7] and by Nelwan [11].

2.4. Matrix performance

Performance of the matrices was computed in the learning set (generation performance) as well as in the test set (reconstruction performance). RMSD performance was expressed in the root-mean-squared differences (RMSD) over leads I-II and V1-V6 between the original Std-ECGs and the constructed ML2Std-ECGs. ECG performance was expressed in the differences (value in the reconstructed ECG minus value in the Std-ECG) in some major ECG characteristics: $QRS_{frontal\ axis}$ (°), magnitude of maximal QRS vector (QRS_{max} (μV)), magnitude of the maximal T vector (T_{max} (μV)), QRS-T spatial angle (SA (°)), spatial ventricular gradient magnitude (SVG_{mag} (mV·ms)) and spatial ventricular gradient magnitude plus orientation ($SVG_{m\&o}$ (mV·ms)). These ECG characteristics were computed by our 3D ECG/VCG analysis program LEADS [14].

Performances were compared with paired or unpaired t-tests, when appropriate. P-values <0.05 were considered significant.

3. Results

3.1. The Leiden 2x2 and 8x8 matrices

The 2x2 and 8x8 Leiden conversion matrices as derived from our learning set are given in Tables 1 and 2.

Table 1. Coefficients of the 2x2 Leiden conversion matrix. ML=Mason-Likar, ML2Std=Reconstructed Standard

	I_{ML}	II_{ML}
I_{ML2Std}	+1.092	+0.075
II_{ML2Std}	-0.082	+0.762

Table 2. Coefficients of the 8x8 Leiden conversion matrix.

	Mason-Likar leads								
Reconstructed leads		I	II	V1	V2	V3	V4	V5	V6
	I	+1.044	-0.106	-0.004	-0.023	+0.035	+0.001	-0.160	+0.407
	II	-0.052	+0.795	+0.048	+0.059	-0.101	+0.042	+0.044	-0.077
	V1	+0.034	-0.024	+0.955	-0.004	+0.047	+0.009	+0.048	-0.173
	V2	+0.034	-0.024	-0.045	+0.996	+0.047	+0.009	+0.048	-0.173
	V3	+0.034	-0.024	-0.045	-0.004	+1.047	+0.009	+0.048	-0.173
	V4	+0.034	-0.024	-0.045	-0.004	+0.047	+1.009	+0.048	-0.173
	V5	+0.034	-0.024	-0.045	-0.004	+0.047	+0.009	+1.048	-0.173
	V6	+0.034	-0.024	-0.045	-0.004	+0.047	+0.009	+0.048	+0.827

3.2. RMSD performance

Figure 1 summarizes the average RMSD performances for the 2x2 and 8x8 Leiden matrices and for the 2x2 Bartosik and Nelwan matrices, expressed as a percentage of the average original RMSD (RMSD between the originally recorded ML-ECGs and Std-ECGs).

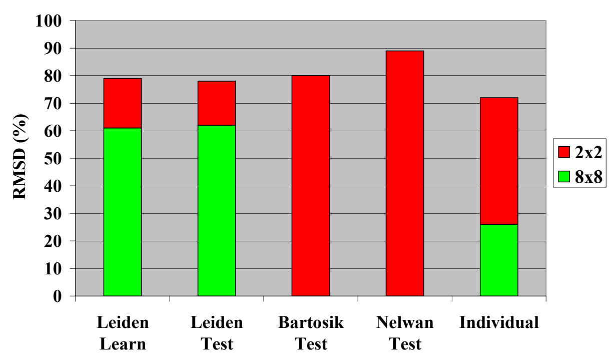

Figure 1. Graphical summary of the 2x2 and 8x8 RMSD performances of the Leiden, Bartosik and Nelwan matrices, expressed as a percentage of the RMSD without correction (ML-ECGs vs Std-ECGs). Performance of the individual conversion matrices is given for comparison.

The RMSD generation (learning set) and reconstruction (test set) performances of the Leiden conversion matrices were nearly the same. With a 2x2 reconstruction, RMSD was reduced to 79% (learning) and 78% (test); with an 8x8 reconstruction the reduction was 61% (learning) and 62% (test). The Bartosik 2x2 reconstruction (reduction till 80%) was of comparable quality as the Leiden 2x2 reconstruction, while the Nelwan reconstruction was qualitatively less favorable (reduction till 89% only). Obviously, individual reconstruction is superior, especially the individual 8x8 reconstruction (RMSD reduction till 26%).

3.3. ECG performance

Table 3 gives a complete performance overview of the Leiden, Bartosik and Nelwan reconstructions. The means of the signed errors give an impression of the amount of bias in the reconstructed ECGs, while the ranges of the signed errors and the means of the absolute errors give an impression of the individual reliability of the reconstructed ECGs. Comparative statistics were done to detect differences between the performances of the 2x2 and 8x8 matrices, and to detect performance differences between the Bartosik and Nelwan matrices on one hand and the 8x8 Leiden matrix on the other hand.

Obviously, all 2x2 reconstructions yield a considerable improvement, while Leiden 8x8 reconstruction offers further improvement. Most of the right axis deviation is removed by a 2x2 reconstruction. However, 8x8 reconstruction decreases the range of the differences between reconstructed and standard ECGs considerably. Similar effects occur in the maximal QRS-complex and T-wave amplitudes. SA, SVG_{mag} and $SVG_{m\&o}$ were benefitted mainly by the 2x2 reconstruction. The general impression is that, depending on the parameter, the Leiden 8x8 matrix performs similar or better than all other 2x2 matrices

4. Discussion and conclusions

In this study we demonstrated that individual reconstruction of the standard ECG from a Mason-Likar ECG yields a considerable RMSD improvement (Figure 1). Individual 8x8 reconstructions are far superior above 2x2 reconstructions; however, in daily practice, this would require that a 15-channel ECG be made in every individual, which is not feasible.

Table 3 shows that all 2x2 matrices yield a considerable gain in RMSD performance and in accuracy of all ECG parameters.

Table 3. RMSD and ECG performances of the Bartosik, Nelwan and Leiden 2x2 and of the Leiden 8x8 conversion matrices in the test set. Errors are the differences between the originally recorded ML-ECGs (column "Original errors") or the reconstructed standard ECGs (other columns) and the originally recorded Std-ECGs. Asterisks in the column headers denote that all listed values in the column differ significantly (P<0.01) from the original errors. Data in each cell are: mean ± SD of the signed errors (upper line), range of the signed errors (between brackets) and mean ± SD of the absolute errors (between parentheses). NS=not significant.

PERFORMANCE MEASURE	ORIGINAL ERRORS	LEIDEN RECONSTRUCTIONS			BARTOSIK & NELWAN RECONSTRUCTIONS			
		$8x8_{Leiden}$*	$2x2_{Leiden}$*	$P_{2x2Leiden}$ vs 8x8Leiden	$2x2_{Bartosik}$*	$P_{2x2Bartosik}$ vs 8x8Leiden	$2x2_{Nelwan}$*	$P_{2x2Nelwan}$ vs 8x8Leiden
RMSD (µV/sample)	34±16 [18–70]	21±12 [8–53]	27±15 [14–70]	<0.001	28±15 [14–69]	<0.001	30±15 [15–75]	<0.001
$QRS_{frontal\ axis}$ (°)	10±8 [-3–64] (11±12)	0±7 [-14–22] (5±5)	-1±9 [-41–18] (5±8)	NS (NS)	3±10 [-15–49] (5±9)	<0.001 (NS)	3±8 [-19–34] (5±7)	<0.001 (NS)
QRS_{max} (µV)	142±120 [-51–421] (146±114)	4±69 [-92–259] (49±48)	11±72 [-80–282] (50±52)	NS (NS)	58±79 [-59–311] (69±70)	<0.001 (<0.05)	31±74 [-68–294] (51±61)	<0.001 (NS)
T_{max} (µV)	27±45 [-58–164] (35±39)	-3±15 [-54–27] (11±11)	-2±20 [-77–48] (13±15)	NS (NS)	10±24 [-70–75] (18±19)	<0.001 (<0.05)	4±24 [-75–69] (16±18)	<0.05 (<0.05)
SA (°)	-3±5 [-14–7] (5±3)	2±4 [-6–14] (3±3)	0±4 [-8–10] (3±2)	NS (NS)	-3±4 [-10–8] (4±2)	<0.001 (<0.05)	-2±3 [-10–5] (3±2)	<0.001 (NS)
SVG_{mag}(mV·ms)	6±8 [-5–31] (7±7)	-2±3 [-10–5] (2±2)	-1±3 [-10–9] (2±2)	NS (NS)	2±4 [-5–14] (3±3)	<0.001 (NS)	1±4 [-8–13] (3±3)	<0.001 (NS)
$SVG_{m\&o}$ (mV·ms)	9±7 [1–36]	5±4 [1–24]	6±4 [0–22]	NS	5±5 [0–25]	NS	5±5 [1–25]	NS

The Leiden 8x8 matrix is superior in RMSD performance (with respect to all 2x2 matrices) and in correction of the frontal QRS axis and QRS- and T-wave amplitudes (especially with respect to the Bartosik and Nelwan matrices). The SA, SVG_{mag} and $SVG_{m\&o}$ are less sensitive to the Mason-Likar electrode placement.

Hence, the overall performance of the Leiden 8x8 matrix is superior: it strongly reduces RMSD, has the smallest positive bias in the QRS frontal axis and in the maximal QRS- and T-wave amplitudes, and "protects" against extreme errors in some individuals.

The differences in the RMSD and ECG performances of the Bartosik, Nelwan and Leiden matrices have to be explained in terms of the differences in the study groups and methodology. The learning set of Bartosik and colleagues consisted of 30 subjects (10 normal, 10 patients with anterior infarction and 10 patients with inferior infarction); further characteristics were not given [7]. The learning set of Nelwan consisted of 30 patients that were admitted to the coronary care unit, suspected of having myocardial infarction [11]. Different from the learning sets of Bartosik and Nelwan, we did not compose our learning set with a certain heart disease in mind, we rather attempted to include a rich variation of BMI/BSA values. Indeed, reconstruction of a Std-ECG from a ML-ECG is a problem of the thoracic electrical transfer function, rather than a problem that relates to the source of the electrical activity (the heart) itself.

Also, the methods to derive the conversion matrices differed. Unfortunately, Bartosik and colleagues and Nelwan and colleagues did not describe in detail how the ECG signals were processed to create a group conversion matrix. We constructed our matrices by linear regression, and used the concatenated ECGs of the whole learning set as the signals in which the linear regression was performed.

Our current study has yielded two matrices, the 2x2 and 8x8 Leiden Mason-Likar to standard ECG conversion matrices, respectively, that may serve to make a full, 12-lead, reconstruction of a standard ECG from a Mason-Likar ECG. The performance of these matrices is better than that of the currently known matrices. Reconstructions with an 8x8 matrix are to be preferred above 2x2 reconstructions of the extremity leads only: it improves the RMSD performance, and improves the reliability of the QRS frontal axis orientation and of the maximal QRS and T amplitudes.

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Address for correspondence:

Cees A. Swenne, PhD
Cardiology Department
Leiden University Medical Center
PO Box 9600
2300 RC Leiden, The Netherlands
email: c.a.swenne@lumc.nl