Comparison of the spatial QRS-T angle derived from digital ECGs recorded using conventional electrode placement with that derived from Mason-Likar electrode position

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Abstract

Background: The spatial QRS-T angle, is ideally derived from orthogonal leads. We compared the spatial QRS-T angle derived from orthogonal leads reconstructed from digital 12-lead ECGs and from digital Holter ECGs recorded with the Mason-Likar (M-L) electrode positions.

Methods and Results: Orthogonal leads were constructed by the inverse Dower method and used to calculate spatial QRS-T angle by (1) a vector method and (2) a net amplitude method, in 100 volunteers.

Spatial QRS-T angles from standard and M-L ECGs differed significantly (57º±18º vs, 48º±20º respectively using net amplitude method and 53º±28º vs, 48º±23º respectively by vector method; $p<0.001$). Difference in amplitudes in leads V4-V6 were also observed between Holter and standard ECGs, probably due to a difference in electrical potential at the central terminal.

Conclusion: Mean spatial QRS-T angles derived from standard and M-L lead systems differed by 5-9º. Though statistically significant, these differences may not be clinically significant.

Keywords: Holter electrocardiography; cardiac repolarization; vectorcardiography; electrode resistance; body surface potential mapping;

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Introduction

Abnormalities of cardiac repolarization have been associated with cardiac arrhythmias and sudden death. QT prolongation due to delayed repolarization due to inherited or acquired conditions is the most well-known example of this.[1] Similarly, transmural repolarization heterogeneity resulting in morphological variants of early repolarization has recently been identified as a risk factor for malignant ventricular arrhythmias.[2] Other repolarization abnormalities linked to life-threatening ventricular arrhythmias include microvolt T wave alternans or presence of a wide, notched T wave.[3] Abnormalities of the transmural sequence of repolarization invariably result in alteration of the shape and direction of the repolarization vector loop with change in T wave axis on the surface ECG. The mean spatial QRS-T angle (the angle between the QRS axis and T wave axis in three dimensions) is normally about 60º for women and 75º for males.[4,5] Widening of the spatial QRS-T angle has been found to be an independent risk factor for cardiac events or mortality[6-8] in conditions like coronary artery disease,[9] systemic hypertension,[10] diabetes mellitus[11] and chronic kidney disease.[12] More recently it has also been thought to be associated with increased mortality even in apparently healthy individuals.[6.7]

Estimation of the spatial QRS-T angle can be made in ECGs recorded using Frank's orthogonal X, Y and Z leads. However, with the increasing use of digital electrocardiographs with considerable signal processing capabilities, the commonly used 12-lead ECG can be transformed to obtain derived orthogonal lead waveforms.[4] The method most commonly used for this purpose is Edenbrandt and Pahlm's matrix transformation model,[13] which uses instantaneous amplitudes of the digital waveforms from leads I, II and V1 to V6 to derive the waveforms in X,Y and Z leads.[4] The spatial QRS-T angle can then be computed from the ECG waveforms in the derived orthogonal leads.

Holter ECGs are being increasingly used in clinical practice and in clinical research studies. While the limb lead electrodes in a standard 12 lead ECG are actually attached to the limbs at the wrists and ankles, the limb lead electrodes in the Holter ECG are attached to the torso instead of the extremities (Mason-Likar configuration) because subjects are ambulatory during the long recording periods.[14] This modified lead placement could potentially alter the spatial orientation of various leads.[15] Whether this substantially affects the reconstruction of the orthogonal leads and the spatial QRS-T angle derived from Holter ECGs is not clear. We therefore compared the spatial QRS-T angles obtained from simultaneously recorded 12-lead digital ECGs and 12-lead Holter ECGs in healthy normal volunteers using two different methods of deriving the spatial QRS and T angles.

Methods

12-lead digital resting ECGs and 12-lead digital Holter ECGs were recorded simultaneously in 100 healthy normal volunteers using dual-snap chest electrodes. The conventional 12-lead digital resting ECGs were recorded using a digital electrocardiograph (Eli 250, Mortara Instrument Inc, Milwaukee, WI) with a sampling rate of 1000 Hz and 12-lead Holters were recorded using H12+ Holter recorder (Mortara Instrument Inc, Milwaukee, WI) with a sampling rate of 1000 Hz. Six dual snap electrodes were used to record chest leads V1 through V6 and were connected to both, the conventional and Holter ECG devices, while limb leads were attached to the torso for the Holter ECGs and at the ankles and wrists for conventional 12-lead ECGs. The subjects were resting in the supine position when the ECGs were recorded. 10-second snapshots were extracted from Holter ECGs at the exact time at which the 12-lead ECGs were recorded using commercially available software (H-scribe, Mortara Instrument Inc, Milwaukee, WI).

All digital ECGs were processed by two methods.

Vector method

A vector method was adopted at the University of Glasgow in the Uni-G algorithm (Version 27.1) which is an automated algorithm for analysis of digital ECGs. Here, the 10-second waveforms for the X, Y and Z leads were formed from the standard 12 lead input data using the inverse Dower technique[13] and an average beat was formed for the X, Y and Z leads as well as the standard 12 leads using time alignment of all the similar beats. The average beats for the X, Y and Z leads were then used to construct the QRS and T vector loops in three dimensions. The direction of the largest instantaneous QRS vector from the QRS loop was considered as the mean direction of the QRS axis. Similarly, the direction of the largest instantaneous T vector from the T loop was considered as the mean direction of the T wave axis. The spatial QRS-T angle was obtained as the difference between these two axes. In addition, the projections of spatial QRS and spatial T axes on the frontal, right sagittal and transverse plane were used to derive the QRS and T angles in the respective planes.

Net amplitude method

All ECGs were also analyzed at the central ECG laboratory of Quintiles Cardiac Safety Services, in Mumbai, India. Median beats for each of the 12 leads were derived in the 12 lead digital and 12 lead Holter ECGs using the Veritas algorithm (Mortara Instrument Inc, Milwaukee, WI). The median beats are composed of median samples (1000 samples /sec) after time alignment of all similar beats in each lead. The digital waveforms of these median beats were used to construct the waveforms of Frank's X, Y and Z leads using Edenbrandt and Pahlm's matrix transformation method.[13] The QRS and T wave amplitudes were manually measured in orthogonal leads X, Y and Z and also in leads V1-V6, I and II in 12-lead digital and 12-lead Holter ECGs by a single expert reader using digital on-screen calipers (CalECG version 2.7, AMPS LLC, NY). The net QRS amplitude was calculated as the R amplitude minus Q or S amplitude (whichever is greater) and the net T wave amplitude as the amplitude of the positive component of the T wave minus the amplitude of the negative component. The spatial QRS-T angles were then calculated from net QRS and T amplitudes in the X, Y and Z leads.[4] QRS and T axes in the frontal, sagittal and transverse planes and their corresponding planar QRS-T angles were also calculated.

Statistical analysis

Spatial and planar QRS-T angles, as well as QRS and T wave amplitudes in individual leads of the 12-lead digital and 12-lead Holter ECGs were compared using the paired T-test. Agreement between the spatial QRS-T angle derived from the 12-lead ECGs and the Holter ECGs was compared by the Bland-Altman limits of agreement. A two-sided α of <0.05 was considered to be statistically significant.

Results

The spatial QRS-T angle in conventional 12-lead ECGs (mean ± SD) was 57°±18° by the net amplitude method (Table 1), which was 9° higher (Bland-Altman limits of agreement -11°, +29°) than that in simultaneously recorded Holter ECGs (Figure 1A). With the vector method, the spatial QRS-T angle in conventional 12-lead ECGs was 53° ± 28° which was 5° higher (Bland-Altman limits of agreement -18°, +28°) than the corresponding angle for 12-lead Holter ECGs (Figure 1B). There were two outliers in this Bland-Altman plot. In both of these cases, the maximum QRS vector was identified as lying in a different quadrant for the conventional 12-lead ECG than for the Holter ECG by the vector method, but not by the net amplitude method.

The QRS and T wave axes in the frontal, right sagittal and transverse planes were also studied (Figure 2). The mean QRS axis in the conventional 12 lead ECG differed from that in the Holter ECGs in the frontal plane by 12° while the T wave axis differed by 10°; the differences in mean QRS and T wave axes for the vector loop method were 13° and 9° respectively. In the sagittal plane, the difference in the QRS and T axes between the digital and Holter ECGs was 6° and 7°

respectively by net amplitude method and 6° and 8° respectively by the vector loop method (Table 1); these differences in the frontal and sagittal planes were statistically significant. In contrast, the differences in the QRS and T axes between the digital and Holter ECGs in the transverse plane were not significantly different (2° and 0° for the net amplitude method and 1° and 0° respectively for vector loop method).

To determine which of the three reconstructed orthogonal leads contribute towards this difference, the net QRS and T wave amplitudes in these leads derived from conventional 12-lead digital ECGs were compared with those derived from 12-lead Holter ECGs by the net amplitude method (Table 2). There was a statistically significant difference in the net amplitude of the QRS complex in all three orthogonal leads derived from 12-lead digital ECGs when compared to that derived from 12-lead Holters. When the difference was expressed in percentage terms, the maximum difference was observed in lead Y followed by Lead Z. A similar finding was also observed for the net T wave amplitude (Table 2).

Data from chest leads V1-V6 and limb leads I and II are used to reconstruct the orthogonal leads in the net amplitude method. Hence, net QRS and T amplitudes in these leads by the conventional 12-lead digital ECGs and 12-lead Holter ECGs were compared (Table 3). Although statistically significant differences were noted in most leads, the differences were smaller (10% or less) for the chest leads (V1-V6) while they were much larger (20 to 50%) for limb leads I and II (Table 3).

Discussion

The Mason–Likar electrode placement system is commonly used for recording Holter ECGs. Mason and Likar originally described the modified lead positions so as to record artifact-free ECGs in ambulatory persons or during exercise testing. While providing reasonably similar morphological waveforms as ECGs obtained using leads placed on the extremities, some authors have found that the frontal QRS and T wave axes may differ in ECGs with modified lead placement. We studied the effect of placement of limb leads on the torso on the spatial QRS-T angle derived from digital ECG signals from Lead I, Lead II and V1 to V6.

Differences in the spatial QRS-T angle derived from conventional and Holter ECGs

We found that there was a statistically significant difference in the spatial QRS-T angle derived from 12-lead ECGs recorded using conventional electrode placements and that from simultaneously recorded 12-lead Holter ECGs using the Mason-Likar lead position. The mean spatial QRS-T angle was 57° by conventional 12 lead ECG versus 48° by 12-lead Holter ECG by the net amplitude method. Similar results were also seen with the spatial QRS-T angle derived from the vector loops; the mean spatial QRS-T angle was 53° by conventional 12 lead ECG versus 48° by 12-lead Holter ECG. The limits of agreement between the two types of lead placements was reasonable, but regardless of whether the net amplitude method or the vector loop method was used to derive the spatial QRS-T angle, the angle obtained by the conventional 12 lead ECG was larger than that obtained by the Holter ECG on average.

Differences in the orthogonal leads derived from conventional and Holter ECGs

In order to identify which of the three reconstructed orthogonal leads contributed to the difference in the spatial QRS-T angle derived from Holter and 12-Lead ECGs, we compared net QRS and T amplitude in the X, Y and Z orthogonal leads derived from each approach. Relatively small differences were seen in the X and Z leads while the maximum difference was observed in lead Y.

Data from 8 ECG leads (Leads I, II and V1-V6) are used to derive the orthogonal leads. Further analysis of these individual leads revealed that the differences in the orthogonal leads occurred because of differences in QRS and T amplitudes in lead I and II. In these leads, the differences in amplitudes between the12-lead and corresponding Holter ECGs ranged from 27 to 55% while differences in the chest leads ranged from 4 to 12%. When data from these 8 leads are used to derive the orthogonal X, Y and Z leads, the amplitudes of waves in leads I and II are given 11% weighting in deriving Lead Z and 14% in deriving lead X but 78% weighting is given when deriving lead Y. It is therefore not surprising that the maximum differences were seen in derived frontal and sagittal plane QRS and T axes which are reconstructed using data from the orthogonal Y lead.

One possible explanation for this observation may be due the relative anatomical position of the limb electrodes. In their original paper, Mason and Likar[14] observed that the QRS and T wave amplitudes were 10 to 20% less in Lead I with the modified leads and 22 to 25% larger in Lead II, consistent with a rightward shift of frontal plane QRS axis. We too observed that the net QRS and T amplitudes was smaller in Lead I and larger in Lead II in Holter ECGs as compared to conventional 12-lead ECGs. While this difference in amplitude may not compromise the diagnostic utility of the modified lead system[16], Jowett et al.[17] found that the frontal plane QRS and T wave axes differed by 25% with standard and modified lead positions, with the axes being more positive with the modified lead placement; we too found higher mean frontal QRS and T axes in Holter ECGs in the present study.

Though the differences in QRS and T waves axes in the sagittal and frontal planes differed significantly between the conventional 12 lead and Holter ECGs, we found that the difference in the spatial QRS-T angle, though statistically significant, was relatively small in magnitude. This is probably because although the modified lead positions had a significant effect on the QRS and T wave axes in the frontal and sagittal planes, this would have affected the QRS and T wave axes to a similar extent. Consequently, difference in the Spatial QRS-T axis was relatively small.

Differences in the QRS and T wave amplitudes in Chest leads from conventional and Holter ECGs

As chest lead recordings were from same dual-snap electrodes for Holter & 12-lead resting ECGs, it was expected that there would not be any difference in the amplitudes of QRS & T wave in the lead V1-V6. However, we found that the QRS and T amplitude in leads V1-V6 showed a small but statistically significant difference in the chest leads too. This difference may have arisen due to differences in the potential of the central terminal which is obtained by joining the left arm, right arm and left leg leads. Schwarzschild et al.[18] and Wilson et al.[19] suggests that the position of the central terminal may differ considerably if the resistance of the body tissues and the contact between the skin and the electrode vary between the three limb electrodes. For example, higher resistance from the left leg electrode will result in a cephalad displacement of the central terminal while a higher resistance in an arm electrode will result in a deviation towards the opposite side of the torso. Spach et al.[20] suggest that changes in lead impedance affect high frequency (QRS complex) and low frequency (T wave) ECG signals differently. Thus the effect of modification of limb lead position on the ECG signal in chest leads seems to be complex, and affects the QRS and T wave complexes in chest leads less than it does in Leads I and II.

The clinical significance of this observed difference in the spatial QRS-T angle would depend on the ability of the two ECG recording methods to classify the spatial QRS-T angle as normal or increased. Various authors have identified cut-off values for the increased spatial QRS-T angle; Kardys et al.[6] have defined an abnormal spatial QRS-T angle as one that exceeds 135° while Rautaharju et al. consider a value >97° as abnormal.[7] Using the criteria by Rautaharju et al., of the 100 ECGs, only 1 subject had a high QRS-T angle on the conventional 12 lead ECG using the net amplitude method; this subject was also classified as having a high QRS-T angle by the vector method. The QRS-T angle was also abnormal on the Holter ECG for this subject using both methods. Using 135° as a cut-off, no ECGs were classified as having increased QRS-T angle.

Conclusion

There is a small but statistically significant difference in the spatial QRS-T angles derived from conventional 12-lead digital ECGs and 12-lead Holter ECGs. This difference is mainly due to differences in QRS and T wave amplitude in reconstructed lead Y and Z leads. A significant proportion of this difference in orthogonal leads is due to differences between Holter and conventional 12-lead recordings for lead I and lead II, resulting from differences in electrode placement for the limb leads. Even though same dual-snap electrodes were used for recording 12-lead and Holter ECGs, the QRS and T amplitudes in lead V4-V6 also differed probably due to difference in the potentials of the central terminals again resulting from the differences in electrode placement. While the spatial QRS-T angle in Holter ECGs did not misclassify any subject as abnormal in the present study where healthy volunteers were studied, since the angle was less than that obtained by the conventional 12-lead ECG in most individuals, it is possible that some individuals with abnormally high QRS-T angles may be misclassified as normal. One of the limitations of our study is that we did not include individuals with heart disease, where the spatial QRS and T axes may vary more widely than in healthy subjects. More studies are needed to assess spatial QRS-T angles in 12-lead ECGs recorded using conventional and Holter ECGs recorded with the Mason-Likar electrode configuration to see how they perform in disease states. Another important question would be whether repositioning the limb electrodes for recording Holter ECGs closer to the limbs, as in the Lund system,[21] will improve the accuracy of the estimated spatial QRS-T angles derived from Holter ECGs.

AUTHORS' DISCLOSURES OF POTENTIAL CONFLICTS OF INTEREST

Employment: Vaibhav Salvi, Gopi Krishna Panicker, Pooja Hingorani, and Snehal Kothari are employees of Quintiles Cardiac Safety Services, Mumbai. **Consultant or Advisory Role:** Dilip Karnad is Consultant to Quintiles Cardiac Safety Services, Mumbai. **Stock Ownership:** None **Honoraria:** None **Research Funding:** None **Expert Testimony:** None **Other Remuneration:** None

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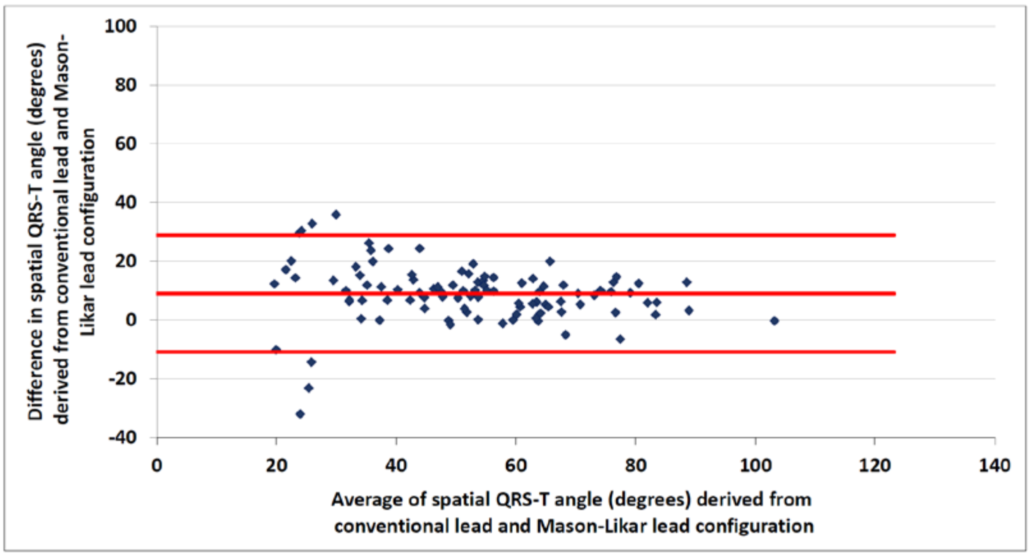
Figure legends

Figure 1: Bland-Altman plot for the spatial QRS-T angle derived from 12-lead ECGs recorded with conventional lead positions and Holter ECGs recorded simultaneously with Mason-Likar lead configuration.

Panel A: Net Amplitude method



Panel B: Vector method

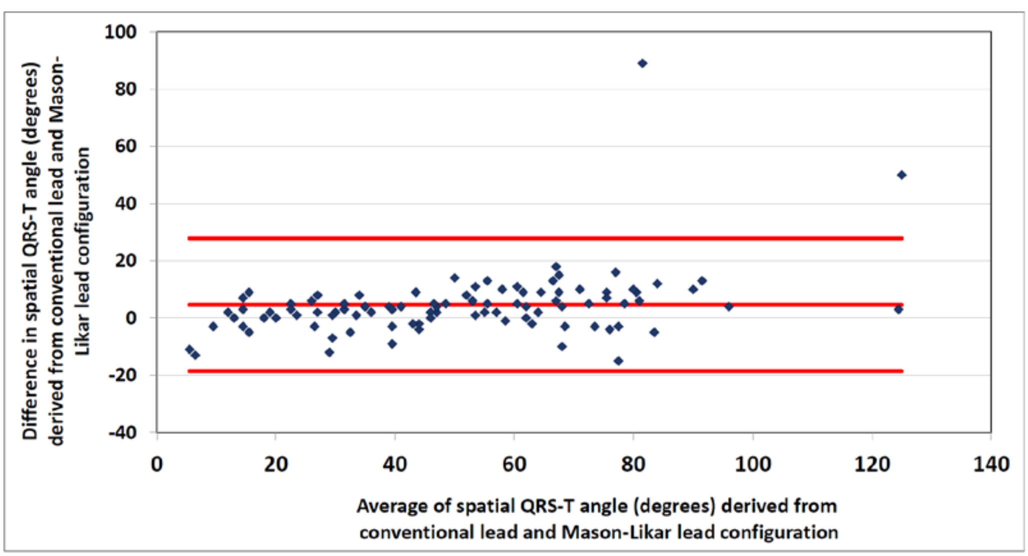
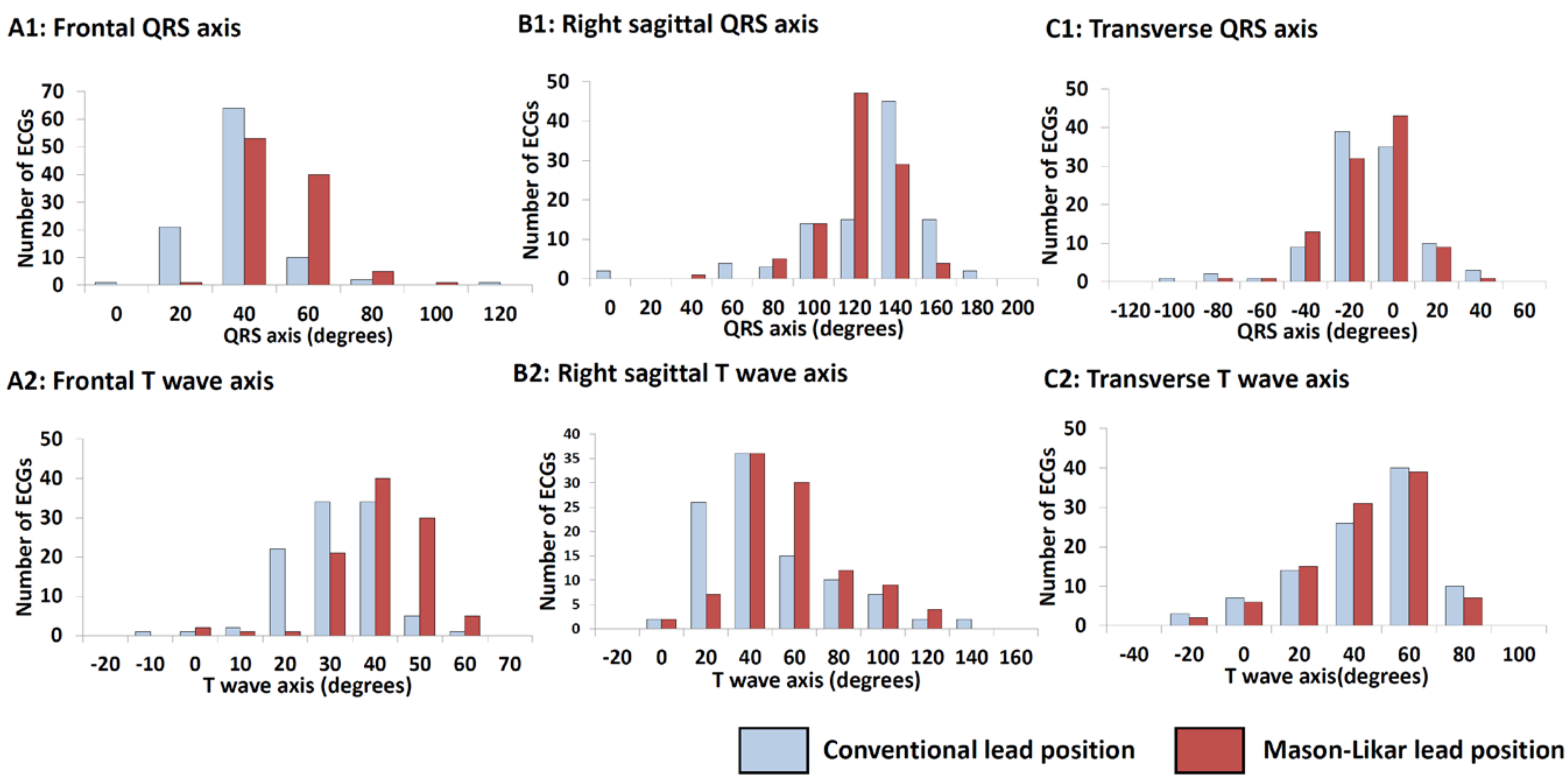


Figure 2: **Histograms of the planar QRS and T wave axis obtained by the vector loop method in 100 ECGs recorded simultaneously using conventional lead positions and the Mason-Likar lead positions. Note that the right sagittal and transverse planar QRS and T axis by both lead systems were similar while the frontal QRS and T wave axis showed a significant rightward bias with the Mason-Likar lead position**



Tables

Table 1: Spatial QRS-T angle and planar QRS and T angles in the frontal, sagittal and transverse planes

	Parameter	Net amplitude method			Vector loop method		
		Conventional ECG	**Holter ECG**	**P value**	**Conventional ECG**	**Holter ECG**	**P value**
1	**Spatial QRS-T angle (^{0})**	57 ± 18	48 ± 20	< 0.001	53 ± 28	48 ± 23	< 0.001
2	**Frontal QRS angle (^{0})**	29 ± 11	41 ± 10	< 0.001	28 ± 22	41 ± 11	< 0.001
3	**Frontal T angle (^{0})**	27 ± 10	37 ± 8	< 0.001	26 ± 11	36 ± 11	< 0.001
4	**Sagittal QRS angle (^{0})**	117 ± 23	111 ± 16	< 0.001	119 ± 29	113 ± 18	< 0.001
5	**Sagittal T angle (^{0})**	39 ± 29	46 ± 23	< 0.001	39 ± 29	47 ± 25	< 0.001
6	**Transverse QRS angle (^{0})**	-18 ± 15	-20 ± 15	< 0.001	-22 ± 22	-21 ± 18	0.339
7	**Transverse T angle (^{0})**	37 ± 21	37 ± 19	0.743	35 ± 23	35 ± 21	0.08

Note: P value is for difference between Holter and Conventional ECG

Table 2: QRS and T wave amplitudes in derived orthogonal leads using the net amplitude method.

	Parameter	Conventional ECG	Holter ECG	Difference (mV)	Difference (Percent)	P value*
1	**QRS amplitude (mV) in lead X (Rx)**	1209 ± 362	1218 ± 376	-9 ± 142	0.74	0.5
2	**QRS amplitude (mV) in lead Y (Ry)**	672 ± 266	1059 ± 365	-387 ± 193	57.58	< 0.001
3	**QRS amplitude (mV) in lead Z (Rz)**	400 ± 380	451 ± 395	-51 ± 125	12.75	< 0.001
4	**T amplitude (mV) in lead X (Tx)**	388 ± 122	413 ± 134	-25 ± 37	6.44	< 0.001
5	**T amplitude (mV) in lead Y (Ty)**	200 ± 86	318 ± 118	-118 ± 51	59	< 0.001
6	**T amplitude (mV) in lead Z (Tz)**	330 ± 184	344 ± 179	-14 ± 49	4.24	0.005

Note: *P value is for difference in mV between Holter and Conventional ECG

Table 3: QRS and T wave amplitudes in the 8 conventional leads (Lead I, II and chest leads V1 to V6) which were used to derive orthogonal leads

	Parameter	Net amplitude method		
		Conventional ECG	Holter ECG	P value
1	**QRS amplitude – lead I (R_I)**	567 ± 324	253 ± 237	< 0.001
2	**T amplitude in lead I (T_I)**	287 ± 95	208 ± 82	< 0.001
3	**QRS amplitude – lead II (R_{II})**	915 ± 297	1248 ± 414	< 0.001
4	**T amplitude in lead II (T_{II})**	357 ± 109	471 ± 148	< 0.001
5	**QRS amplitude – lead V1 (R_{V1})**	-606 ± 461	-575 ± 413	0.06
6	**T amplitude in lead V1 (T_{V1})**	66 ± 187	79 ± 168	0.03
7	**QRS amplitude – lead V2 (R_{V2})**	-621 ± 632	-649 ± 593	0.1
8	**T amplitude in lead V2 (T_{V2})**	678 ± 313	702 ± 317	0.006
9	**QRS amplitude – lead V3 (R_{V3})**	370 ± 711	329 ± 674	0.2
10	**T amplitude in lead V3 (T_{V3})**	675 ± 261	726 ± 269	< 0.001
11	**QRS amplitude – lead V4 (R_{V4})**	1277 ± 606	1337 ± 655	0.01
12	**T amplitude in lead V4 (T_{V4})**	594 ± 200	663 ± 232	< 0.001
13	**QRS amplitude – lead V5 (R_{V5})**	1391 ± 458	1549 ± 525	< 0.001
14	**T amplitude in lead V5 (T_{V5})**	471 ± 147	528 ± 172	< 0.001
15	**QRS amplitude – lead V6 (R_{V6})**	1115 ± 338	1244 ± 390	< 0.001
16	**T amplitude in lead V6 (T_{V6})**	356 ± 115	395 ± 134	< 0.001

Note: P value is for difference between Holter and Conventional ECG