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EVALUATION OF PERFORMANCE AND SAFETY OF THE 12-LEAD ECG: A PROSPECTIVE SIMULTANEOUS PAIRED COMPARATIVE STUDY

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Abstract: This prospective, paired comparative study aimed to evaluate the diagnostic accuracy and safety of a multi-channel digital ECG system (Zoncare company, E-Series) against a conventional device (ED** company, SE-Series) in a clinical setting. A total of 154 participants were categorized into three groups—normal ECG, arrhythmia, and ST-segment elevation/depression—and underwent sequential ECG recordings with both devices in randomized order. Key parameters, including heart rate, PR interval, QRS duration, QT interval, and the axes of the P wave, QRS complex, and T wave, and ST-segment deviation, were automatically measured by both systems, with ST-deviation also assessed manually. Results indicated no statistically significant differences ($P > 0.05$) in any parameter between the two devices. Manual evaluation confirmed 100% recognition accuracy of ST-segment elevation or depression by the E-Series, with no significant difference in deviation magnitude ($P > 0.05$). Automatic measurements exhibited exceptionally high inter-device correlation, with r-values approaching 1 (all $P < 0.001$). No device-related adverse events were recorded throughout the study. In conclusion, the Zoncare E-Series multi-channel digital ECG system demonstrated diagnostic non-inferiority compared to the conventional reference device across a spectrum of cardiac rhythms and ischemic manifestations, supporting its reliability and safety for clinical electrocardiographic acquisition.
Keywords: Accuracy; Electrocardiograph; Multichannel; ECG parameters; ST-segment deviation; Arrhythmias; Safety

1 INTRODUCTION

Cardiovascular diseases, characterized by high morbidity and mortality, pose a serious threat to human health. Early diagnosis and timely treatment are crucial for improving patients' quality of life. The electrocardiogram (ECG) is a technique that uses an electrocardiograph to record the heart's electrical activity from the body surface during each cardiac cycle, capturing the bioelectrical signals generated by myocardial activation. Currently, digital multi-channel electrocardiographs are widely used in the clinical diagnosis of heart diseases to record and analyze ECG waveforms and their periodic characteristics. These devices offer rapid response times, measurement functionality, and can immediately print ECG waveforms. They are particularly suitable for recording persistent abnormal ECG activity and conducting emergency cardiac examinations, making them the most widely used method for cardiac function testing. With advancements in medical technology, the requirements for the measurement accuracy of ECG devices have become increasingly stringent.

This study aimed to identify potential risks associated with the E-Series digital multi-channel electrocardiograph across diverse and complex user groups in real clinical settings. Furthermore, through a comparative study with the ED** SE series electrocardiographs, the equivalence and safety of the E-Series digital multi-channel electrocardiograph in subjects with normal ECG, arrhythmias, and ST-segment elevation or depression were validated to confirm its clinical applicability.

2 METHODS

2.1 Study Design

This was a prospective, simultaneous paired comparison study. The study protocol was developed in accordance with ISO 14155:2020 [1], the NMPA (National Medical Products Administration,China) Guidelines for Clinical Trial Design of Medical Devices (2018) [2], and relevant sections of the following standards:

(1) IEC 60601-2-25:2011 [3], Article 201.12.1.101, which specifies performance requirements for the automatic measurement function of electrocardiographs;

(Note： In its clauses regarding the performance evaluation of automated measurement functions, although it does not explicitly state “using manual measurements as the standard,” it requires that the accuracy of automated measurements by the device must be compared against "recognized measurement methods." In the field of clinical electrocardiography, "manual measurements performed by experienced physicians" are the recognized reference method.)

(2) GB 9706.225-2021 [4], which defines standards and regulations for electrocardiogram signal measurement.

The study's sample size was determined following the NMPA Guidelines for Clinical Trial Design of Medical Devices (2018) .The randomized matching design method was adopted in this study, and the patients were self-controlled.

2.2 Subjects

A total of 154 subjects were enrolled in this study. Researchers assigned a unique number to each subject in the order of inclusion, which remained unchanged throughout the study. Based on the initial outpatient ECG diagnosis, subjects were divided into three groups: ① Normal ECG Group (Group N, n=54), ② Arrhythmia Group (Group A, n=50), and ③ ST-Segment Elevation or Depression Group (Group S, n=50).

Inclusion Criteria: 1) Age ≥3 years, gender not limited; 2) Subjects meeting any one of the following criteria: a. Electrocardiographically normal subjects; b. Arrhythmia: atrial or ventricular premature beats; atrial flutter/fibrillation or first-degree atrioventricular block and complete left/right bundle branch block; c. Presence of ST-segment elevation ≥0.2 mV or depression ≥0.1 mV in two adjacent leads[5]; 3) good cooperation, able to cooperate to complete this study; 4) Voluntary and having provided signed informed consent.

Exclusion Criteria: 1) Patients with a pacemaker or implantable cardioverter-defibrillator (ICD); 2) Patients with tremors or Huntington's disease and other conditions making it difficult to remain still and cooperate with the examination; 3) Patients with bullous diseases or extensive systemic skin rashes unfavorable for surface electrode recording; 4) Patients with known allergy to skin disinfection alcohol; 5) Patients with skin infectious diseases; 6) Patients with a history of mental illness or cognitive dysfunction; 7) Patients who participated in other clinical trials within 30 days that might affect this test; 8) Researchers' judgment of other circumstances unfavorable for the test.

2.3 Devices

The test device was the Zoncare E120 Digital Multi-Channel Electrocardiograph (made by Wuhan Zoncare Bio-Medical Electronics Co., Ltd.). The control device was the ED** SE-12**pro Digital Electrocardiograph (made by ED** Instruments, Inc.).

2.4 Experimental Methods

2.4.1 Sampling period for inclusion

All enrolled patients underwent electrocardiogram (ECG) examinations in a random order. The lead wires of Zoncare E120 and ED** SE-12**pro were connected to the same set of patient electrodes to ensure that both devices simultaneously collected the same physiological signals. Under the same parameter conditions, conventional 12-lead ECG signals were simultaneously collected from the same subject. A total of three sets of continuous synchronous records were obtained. The data were stored and printed, see Figure 1.

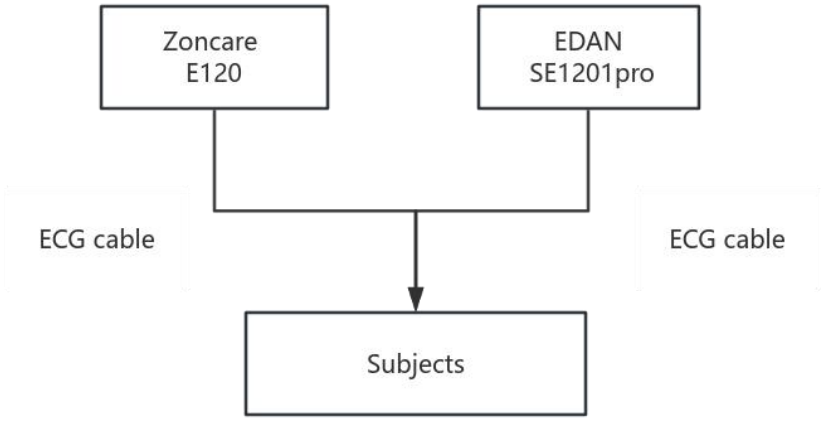

Figure 1 Flowchart of the Operation of Electrocardiogram Clinical Research

2.4.2 Analysis and diagnosis period

1) After sample collection, all subject ECGs were compiled, and their identifiers were anonymized before the ECGs were compiled into separate volumes.

2) This study utilized expert consensus under a blinded method as the reference standard. Two ECG experts will independently diagnose the ECGs. If their diagnoses are consistent, the analysis proceeded to the next measurement stage; if their diagnoses differ, a third expert will be consulted for a final diagnosis.

3) Measured parameters included heart rate, PR interval, QRS duration, QT interval, QTc value, P-wave axis, QRS axis, T-wave axis, and the distance of the ST segment from the baseline. For those diagnosed with normal ECGs, further manual measurements will be taken for heart rate, PR interval, QRS duration, QT/QTc interval, P wave amplitude, QRS height, T wave amplitude, and the distance between the ST segment and the baseline, see Table 1.

4) In the arrhythmia group, manual measurement was used as the gold standard: the PR interval was measured manually

for those diagnosed with first degree atrioventricular block; QRS duration was measured manually for patients diagnosed with complete bundle branch block. For those diagnosed with ST segment elevation or depression, the amplitude of ST segment elevation or depression in the same lead was measured manually. The above values are the average values of the manually measured values from two experts, see Table 1.

Table 1 Parameters of Automatic Measurement and Manual Measurement by ECG Machine under Test

Items	Parameter	Equipment measurement parameters	Artificial repetition measurement parameters	Arrhythmia secondary artificial repetition measurement parameters	Related symptoms
1	heart rate	√	√	√	-
2	PR interval	√	√	√	first degree a-v block
3	QRS duration	√	√	√	Complete bundle branch block
4	QT interval	√	√	√	-
5	QTc value	√	/	/	-
6	P wave electrical axis	√	/	/	-
7	QRS axis	√	/	/	-
8	T-wave electrical axis	√	/	/	-
9	Distance of the ST segment from the baseline	/	√	√	ST segment elevation or depression

2.4.3 Endpoint criteria

The primary endpoint was the consistency of automatically measured parameters between devices. Secondary endpoints included:

1). Accuracy compared to manual measurement (gold standard);

2).Accuracy in identifying ST-segment deviation;

3).Incidence of adverse events and device failures.

2.5 Evaluation Methodology

2.5.1 Safety evaluation index

(1)Safety evaluation index 1 (S1) : instrument failure rate.

Recording time: The start time is defined as the first subject's use of the test equipment, and the end time is the last subject's use of the equipment.

Analysis method: The instrument failure rate is analyzed based on recorded instrument malfunctions during testing, and the safety of the test equipment is calculated accordingly.

$$\lambda = F / T$$

Among them:

λ(lambda)represents the failure rate, typically expressed as the number of failures per hour or per thousand hours.

F represents the number of failures that occurred during the observation period.

T Represents the total operating time (usually in hours) of a device or system.

(2)Safety evaluation index 2 (S2) : incidence of adverse events and serious adverse events

Recording time: The start time is defined as the first subject's use of the test equipment, and the end time is the last subject's use of the equipment.

Method:Adverse events (AEs) and serious adverse events (SAEs) are recorded and analyzed for incidence. The safety of the test equipment is then evaluated based on this data.

Incidence of AE = (Number of AE cases / Total number of subjects) * 100%

Incidence of SAE = (Number of SAE cases / Total number of subjects) * 100%

2.5.2 Accuracy evaluation index

(1) Accuracy Evaluation Index 1 (P1): Consistency Rate.

The E-series digital multichannel electrocardiograph and ED** electrocardiograph measured eight basic parameters: heart rate, PR interval, QRS duration, QT interval, QTc value, P wave axis, QRS axis, and T wave axis. The measurement results demonstrated strong consistency.

(2)Accuracy Evaluation Index 2 (P2): Accuracy.

The parameter measurement accuracy of the E series electrocardiogram machine was quantified by the following endpoint indicators:

Comparison of Waveform Parameter Measurement Results Strongly Correlated with Arrhythmia and Myocardial

Ischemia.
Time Parameters: Comparative analysis of the automatic measurement values of the E series electrocardiograph and the manual measurement values (gold standard) of experts in heart rate, PR interval, QRS duration, and QT interval, calculated in milliseconds (ms).
Amplitude Parameters: Differences in manual measurement results of the E series electrocardiograph and ED** electrocardiograph when the ST segment offset amplitude (elevation/depression) occurs.
(3)Accuracy Evaluation Index 3 (P3): Correlation of measurement parameters.
The E series digital multi-channel electrocardiograph is highly consistent with the reference equipment in terms of measurement parameters and the ability to identify ST segment elevation or depression.

2.6 Statistical Approach

The analysis was conducted using SPSS 28.0 statistical software.
Conform to the clinical plan: meeting the requirements of testing scheme and inclusion criteria, All cases were completed as planned, consistent with the research protocol;
Safety analysis set: includes all randomized participants who used the research instruments and underwent safety evaluation, forming the safety analysis set of the current study;
1.Measurement data are presented as mean ± standard deviation or median (interquartile range). Differences between devices were compared using paired t-tests (for normally distributed data) or Wilcoxon signed-rank tests (for non-normally distributed data); differences between automatic and manual measurements were analyzed with paired t-tests (for normally distributed data) or Wilcoxon signed-rank tests (for non-normally distributed data).
2.Correlation analysis was conducted using Pearson's method[6].

2.7 Sample Size Calculation

This test is an equivalence test, and the sample size estimation can be calculated according to formula 1:

$$n_c=\frac{2(Z_{1-\alpha/2}+Z_{1-\beta/2})^2\sigma^2}{(\delta-|u_t-u_c|)^2} \quad (1)$$

Comments:

- $\mathbf{n_c}$: The total number of subjects required;
- $\mathbf{Z_{1-\alpha/2}}$ and $\mathbf{Z_{1-\beta/2}}$: Percentiles corresponding to 1-α/2 and 1-β/2 in the standard normal distribution;
- **δ**: Equivalent cut-off value;
- u_t: Mean value of experimental group;

u_c: The mean value of control group;

- **σ**: The two combinations are equal in standard deviation.

This study is an equivalence test. Based on the results from previous literature[7], the average values of the experimental group and the control group were 64.38 and 64.27 respectively, and the difference value ut-uc was 0.11. The standard deviations of the experimental group and the control group were 1.95 and 1.88 respectively, and the calculated combined standard deviation s was 1.91. According to the clinical manifestations of this product, clinical experts determined the equivalence threshold to be 1. In this study, α = 0.05, β = 0.1, and the result calculated according to the formula is:

$$n_c=2(Z_{1-\alpha/2}+Z_{1-\beta/2})^2\sigma^2/(\delta-|u_t-u_c|)^2\approx120 \quad (2)$$

After calculation, we get a sample size of 120, taking into account the 20% dropout rate, the final sample size is at least 144.

3 RESULTS

3.1 Baseline Characteristics

A total of 154 subjects participated in the clinical study: 54 with normal ECGs, 50 with arrhythmias, and 50 with ST-segment changes (elevation or depression). No instrument malfunctions occurred during the study, and no adverse events (such as electric shock, skin allergies, or infections) were reported during the use of the test equipment.

3.2 Comparison of Automatic Measurements Between E120 and SE-12**pro Devices

The comparison of eight basic parameters (heart rate, PR interval, QRS duration, QT interval, QTc value, P-wave axis, QRS axis, T-wave axis) automatically measured by the E120 and the ED** SE-12**pro showed strong consistency, with no statistically significant differences observed. Detailed results are presented in Table 2.

Table 2 Comparison of Basic Measurement Values between Zoncare E120 and ED** SE-12**pro

Items	Zoncare E120(n=154)	ED** SE-12**Pro(n=154)	P-value
heart rate (bpm)	74.6±15.6	74.6±15.7	1.00
PR interval (ms)	155.3±25.1	155.5±24.7	0.68
QRS duration(ms)	89.8±8.8	88.9±8.2	0.12
QT interval (ms)	395.7±36.5	395.4±38.0	0.79
QTc value (ms)	422.9±21.4	425.0±19.8	0.11
P wave electrical axis (°)	60.0(46.8,66.0)	56.5(39.0,67.0)	0.17
QRS axis (°)	43.7±32.0	44.5±32.3	0.29
T-wave electrical axis (°)	43.5±42.6	44.1±43.1	0.47

Note: Data are presented as mean ± SD or median (IQR)

3.3 Comparison Between Test Device and Expert Manual Measurements

The comparative analysis between the E120 and expert manual measurements (gold standard) revealed no statistically significant differences in various parameters within the arrhythmia group and the ST-segment change group. Detailed results are presented in Table 3.

Table 3 Comparison between Zoncare E120 and Expert Manual Measurement Values (Gold Standard)

Parameter	Group	Zoncare E120(Auto)	Manual measurement	P-value
heart rate(bpm)	Arrhythmia (n=50)	77.9±17.2	77.7±17.3	0.20
	ST Change (n=50)	74.6±15.6	74.7±15.6	0.15
PR interval (ms)	Arrhythmia (n=50)	156.4±24.7	154.6±24.5	0.07
	ST Change (n=50)	155.3±25.1	156.6±24.2	0.13
QRS duration(ms)	Arrhythmia (n=50)	90.8±8.1	90.5±8.9	0.41
	ST Change (n=50)	89.8±8.8	89.3±8.1	0.28
QT interval (ms)	Arrhythmia (n=50)	402.2±39.3	401.0±39.6	0.07
	ST Change (n=50)	394.7±36.5	396.9±35.1	0.12

Note: Auto: Automatic measurement by the device. Manual: Gold standard manual measurement by experts.

3.4 Comparison of ST-Segment Change Amplitude Measurements

The Zoncare E120 and ED** SE-12**pro devices showed no false negative or false positive cases in identifying ST segment elevation or depression. There were no statistically significant differences observed in the corresponding ST segment parameters between the two groups. The detailed results are presented in Table 4.

Table 4 Comparison of Automatic Measurement Values for ST-Segment Changes between Zoncare E120 and ED** SE-12**pro

items	Zoncare(n=50)	ED**(n=50)	P-value
Number of Leads with Elevation (n=21)	3.8±1.3	3.8±1.2	0.32
Maximum elevation(mV)	0.9±0.2	0.9±0.1	0.20
Number of Leads with Depression (n=29)	4.0±1.4	4.0±1.3	0.33
Maximum depression(mV)	0.5(0.5,0.8)	0.5(0.5,0.9)	0.56

3.5 Correlation Analysis Between Test and Reference Models

Correlation analysis of the automatic measurements from the Zoncare E120 and the ED** SE-12**pro revealed that the correlation coefficient (r) values for all parameters were close to 1, with P-values less than 0.001, indicating a strong correlation. Detailed results are presented in Table 5.

Table 5 Correlation Analysis Results of Automatic Measurement Values between E120 and ED** SE-12**pro

Items	Normal ECG(n=54)		Arrhythmia group(n=50)		ST segment change group(n=50)	
	R-value	P-value	R-value	P-value	R-value	P-value
Heart rate	0.999	<0.001	0.998	<0.001	0.997	<0.001
PR interval	0.989	<0.001	0.982	<0.001	0.902	<0.001
QRS duration	0.893	<0.001	0.887	<0.001	0.982	<0.001

Items	Normal ECG(n=54)		Arrhythmia group(n=50)		ST segment change group(n=50)	
	R-value	P-value	R-value	P-value	R-value	P-value
QT interval	0.984	<0.001	0.987	<0.001	0.999	<0.001
QTc value	0.904	<0.001	0.901	<0.001	0.983	<0.001
P wave electrical axis	0.930	<0.001	0.989	<0.001	0.983	<0.001
QRS axis	0.987	<0.001	0.996	<0.001	0.999	<0.001
T-wave electrical axis	0.991	<0.001	0.995	<0.001	0.997	<0.001

3.6 Adverse Events

No adverse events or associated effects were observed during this trial.

4 DISCUSSION

The accuracy of automatic electrocardiogram (ECG) measurements is a critical factor in the international standardization and quantification of ECG devices[8]. Automatic measurement of ECG parameters encompasses amplitude, interval, and noise resistance stability. The accuracy of these parameters directly impacts ECG interpretation and subsequent medical decisions[9]. In the previous laboratory research, 100 sets of real human data from the EU "General Standard for Electrocardiogram" database were input into the product to be tested and the comparison product. Then, the P-wave time, PR interval, QRS time and QT interval were compared with the final reference values of CSE data. The comparison indicators were the average deviation and standard deviation[10]. By comparing the data of the product to be tested and the comparison product, the conclusion was drawn: the average deviation and standard deviation of both products met the requirements of Clause 201.12.1.101 of IEC60601-2-25: 2011, meeting the measurement accuracy requirements, and it was confirmed that the two products were exactly the same.

The results of this clinical study indicate that the E-Series Digital Multi-Channel Electrocardiograph met the anticipated research objectives. Analysis demonstrated strong consistency in eight fundamental ECG parameters measured by the E-Series device compared to the ED** SE series device, with no statistically significant differences ($P > 0.05$). For ST-segment deviation. The E-Series device demonstrated 100% accuracy in detecting ST-segment deviations, with the measured amplitudes showing no significant difference from manual measurements ($P > 0.05$). Correlation analysis further confirmed a high degree of correlation between the automatic measurements of both devices (r values close to 1, $P < 0.001$). Furthermore, no adverse events such as electric shock injury, skin allergy, or infection were observed during the use of the test equipment in 154 patients.

The significant correlation observed in this study (with an r value close to 1) and the perfect recognition rate of ST segment deviations (100%) are comparable to the results of previous laboratory validation studies on electrocardiogram devices. The results of this study, particularly for key parameters such as QT interval and ST segment amplitude, show the superior consistency of measurements on the E-series platform. Additionally, the 100% accuracy of automatic ST segment elevation/lowering detection is consistent with the performance benchmarks in previous literature on standardized electrocardiogram analysis, and even exceeds these benchmarks. The accuracy of ST segment assessment is clinically crucial as it is directly related to the reliable diagnosis of myocardial ischemia and infarction, and the diagnostic accuracy directly affects the treatment path and patient prognosis. Clinical trial results indicates that the E-series device can provide reliable automatic measurement values, which has the potential to reduce differences among different observers and improve the reliability of diagnosis in busy clinical settings, especially when immediate professional manual review is not available.

Although the research results are convincing, this study still has some limitations. Firstly, the sample size may not be sufficient for subgroup analysis of rare arrhythmias. Secondly, the study cannot fully simulate the situation of using a single device alone in routine clinical practice. Future research should evaluate the performance of the E series devices in independent usage scenarios, especially in high-activity environments such as emergency rooms or ambulances. Finally, this study was conducted in a single center. Multi-center trials will help confirm the general applicability of the research results in different patient populations and clinical settings.

5 CONCLUSION

This prospective paired comparative study provides robust evidence that the Zoncare E-Series Digital Multi-Channel Electrocardiograph shows high consistency and safety, supporting its clinical use when compared to the reference device(ED** SE-12**pro). The comprehensive evaluation across different subject groups demonstrated:

1.Diagnostic Performance: High consistency and high correlation of automatically measured parameters with the reference device across all test groups (normal, arrhythmia, ST-segment change). ST-segment deviation recognition accuracy reached 100%.

2.Operational Safety: Zero device-related adverse events across 154 clinical applications. No operational failures or stability issues were observed.

3.Clinical Utility: Demonstrated reliability in diagnosing various cardiac rhythms and ischemic patterns, enabling seamless integration into existing clinical workflows.

These findings validate the Zoncare E-Series Digital Multi-Channel Electrocardiograph as a clinically equivalent and reliable alternative to established ECG systems.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

CLINICAL TRIAL REGISTRATION

This study was registered at the Chinese Clinical Trial Registry (ChiCTR), with the registration number: ChiCTR2500105711. The full registration information can be accessed online at: https://www.chictr.org.cn/bin/project/edit?pid=274002

ETHICS STATEMENT

This clinical study complies with the ethical principles derived from the Declaration of Helsinki, the international standard ISO 14155:2020, and other applicable national standards. It was implemented after passing the ethics review, and the study protocol was not modified.

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