A New Method in Short-Term Heart Rate Variability—Five-Class Density Histogram

Liping Li, Ke Li, Changchun Liu, Chengyu Liu and Yuanyang Li

Abstract—A five-class density histogram with an index named cumulative density was proposed to analyze the short-term HRV. 150 subjects participated in the test, falling into three groups with equal numbers -- the healthy young group (Young), the healthy old group (Old), and the group of patients with congestive heart failure (CHF). Results of multiple comparisons showed a significant differences of the cumulative density in the three groups, with values 0.0238 for Young, 0.0406 for Old and 0.0732 for CHF (p<0.001). After 7 days and 14 days, 46 subjects from the Young and Old groups were retested twice following the same test protocol. Results showed good-to-excellent interclass correlations (ICC=0.783, 95% confidence interval 0.676-0.864). The Bland-Altman plots were used to reexamine the test-retest reliability. In conclusion, the method proposed could be a valid and reliable method to the short-term HRV assessment.

Keywords—autonomic nervous system, congestive heart failure, heart rate variability, histogram

I. INTRODUCTION

HEART rate variability (HRV), a measurement of the beat-to-beat variations in instantaneous heart rate or R-R intervals, is regarded as an indicator of the health status of autonomic nervous system[1]-[4]. Histogram, a geometrical method displaying frequency distribution, is an effective tool that has been widely used in long-term HRV[1].

The histogram is particularly suitable for the long-term HRV because of its ease to implement and relative insensitivity to the quality of the R-R interval series[1], [2]. Moreover, the artefacts outside the triangle are capable to reduce the dependency of preprocessing[3], [5]. The major disadvantage of the histogram, however, is the exigency to the length of the series. In practice, recordings of at least 20 min, preferably 24h should be used to ensure the correct performance of the histogram[1], [2]. A too short series usually influences the reliability of this method.

In this study, a new type of histogram named five-class density histogram with a new quantitative index – the cumulative density was proposed. It has been testified as an effective method in analysis of short-term HRV with a duration of only five to ten minutes. The validity and reliability of this method were also examined by statistical analyses on R-R interval series of subjects in three groups.

II. METHODS

A. Data Acquisition

One hundred and fifty subjects aged between 18 and 80 years old participated in this study. The subjects fell into three groups -- the healthy young group (Young), the healthy old group (Old), and the group of patients with congestive heart failure (CHF), with equal number in each group. Subjects from Young were under the age of 35 whereas those from Old were over the age of 45. The subjects in CHF group were accord with the classes II - III of the New York Heart Association (NYHA) Functional Classification.

All tests took place in a quiet room at a controlled temperature of 22°C. Participants were firstly asked to lie supine on a clinical bed for a 10-minute rest prior to experiment. Then, a standard limb Ⅱ leads ECG were recorded for 5 to 10 minutes using a cardiovascular system status monitor (CVFD-I) developed by Institute of Biomedical Engineering, Shandong University, at a sampling frequency of 1000 Hz. A band-pass filter with 0.05Hz-125 Hz was used for signal filtering. The R-R interval series were constituted from the R-peaks extracted from the ECG signal using the wavelet transform modulus maxima[6], [7]. A preprocessing is employed to remove the artefacts that could lead to statistical bias in HRV analysis[8]-[11]. Subsequently the five-class density histogram was constructed and the new index cumulative density was obtained. The flow chart of the procedure above has been displayed in Fig. 1. After 7 and 14 days, some young and elderly healthy participants were retested twice following the same protocol in order to assess the reliability of the method.

B. Preprocessing of R-R Interval Series

A number of factors influence the quality of R-R interval series, such as the detector errors that were most commonly caused by the presence of noise, baseline wander, high amplitude T wave, low amplitude QRS, etc.[8]. In addition, the ectopic and occasional arrhythmias frequently appear in the ECG recording[9]. Thus, some preprocessing techniques are required in a reliable HRV test, especially short-term HRV. One method that is well-suited to such preprocessing is the impulse rejection filter proposed by McNames J *et al*.[10]. This method bears advantages in ease of use, but it can be easily affected by the non-stationary trend of R-R interval series. Thus an improved method proposed in our previous study was used in this paper[11].

Liping LI, Ke LI, Changchun LIU and Chengyu LIU are with the Institute of Biomedical Engineering, Shandong University, P. R. China.
Yuanyang LI is with the Biomedical Engineering Dept, Provincial Hospital affiliated to Shandong University, P.R.China.
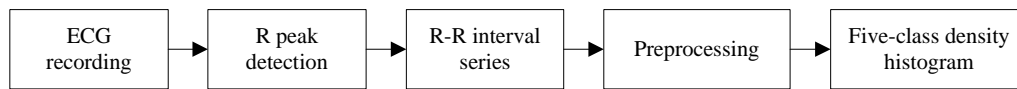Corresponding author: Changchun LIU, e-mail: changchunliu@sdu.edu.cn.

Fig. 1 Flow chart for procedure of experiment and data analysis

C. The Five-class Density Histogram and Cumulative Density

Given the filtered R-R interval series $S' = \{s_1, s_2, \cdots, s_M\}$, where M is the series length, the five-class density histogram is constructed as follows:

① The range of the series s_{range} can be calculated as: $s_{range} = s_{max} - s_{min}$, where s_{max}, s_{min}, represents the maximum and the minimum of the series respectively.

② The left-step-length H_l and the right-step-length H_r are defined as (1),

$$H_l = \frac{s_{median} - (s_{min} + a)}{5} , \quad H_r = \frac{(s_{max} - a) - s_{median}}{5} , \quad (1)$$

where s_{median} represents the median of the series and $a = 0.1 * s_{range}$ is a predetermined value.

③ Supposing $s_i (i=1,2,..., M)$ is the element of the R-R interval series, then the elements are classified into five classes. The conditions, range and element number of each class are shown in Table 1.

④ The percentage of the elements in each class is defined as:

$$p_i = \frac{N_i}{M} , \quad i = 1, 2, \cdots, 5 , \quad (2)$$

in which, N_i is the element number of each class and M is the length of the R-R interval series.

⑤ Then, the distribution density of each class is calculated as in Eq. 3,

$$\rho_i = \frac{p_i}{r_i} , \quad i = 1, 2, \cdots, 5 , \quad (3)$$

where p_i is the percentage of the elements in each class, r_i is the class range and ρ_i is the distribution density of the corresponding class.

⑥ A cumulative density is defined as the sum of distribution density of the five classes, as follows,

$$\rho_c = \sum_{i=1}^{5} \rho_i . \quad (4)$$

TABLE I
CONDITIONS, RANGES AND ELEMENT NUMBERS OF THE FIVE CLASSES.

Classes	Conditions	Range	Element Number
Class 1	$s_{min} + a \leq s_i < s_{median} - 3 * H_l$	$r_1 = 2 * H_l$	N_1
Class 2	$s_{median} - 3 * H_l \leq s_i < s_{median} - H_l$	$r_2 = 2 * H_l$	N_2
Class 3	$s_{median} - H_l \leq s_i < s_{median} + H_r$	$r_3 = H_l + H_r$	N_3
Class 4	$s_{median} + H_r \leq s_i < s_{median} + 3 * H_r$	$r_4 = 2 * H_r$	N_4
Class 5	$s_{median} + 3 * H_r \leq s_i < s_{max} - a$	$r_5 = 2 * H_r$	N_5

D. Statistical Analysis

All statistical analyses were performed using the Statistical Package for Social Sciences (V16, SPSS Inc., Chicago, IL, USA). Data were assessed for normality using the Kolmogorov-Smirnov test. A one-way ANOVA test was applied to test for differences between patients and control groups as well as between age groups. A box-plot was used to summarize the data in graphic form. The interclass correlation coefficient (ICC) was computed to assess the reliability of algorithms. The reliability was considered to be moderate if the ICC was between 0.60 and 0.80 and to be high-leveled in if the ICC was higher than 0.80[12], [13]. In addition, Bland-Altman plots were also applied to assess the reliability of the method. All results were considered as statistically significant for p<0.05.
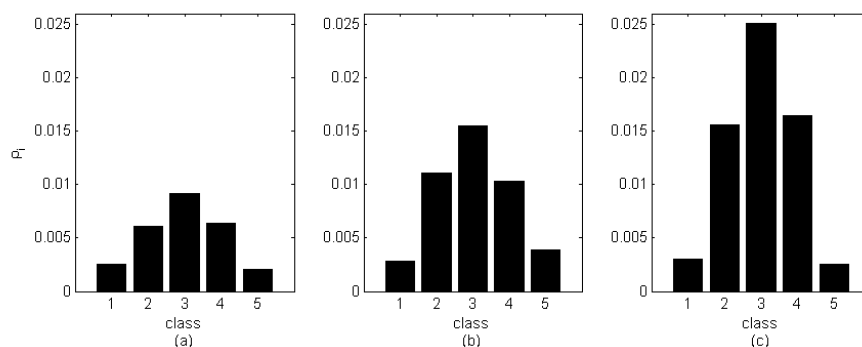

Fig. 2 Three examples of typical five-class density histograms: (a) a subject from the Young group (ρ_c =0.026), (b) a subject from the Old group (ρ_c =0.044), and (c) a subject from the CHF group (ρ_c =0.063)

III. RESULTS

A. Results of Five-class Density Histogram

Examples of five-class density histogram for three contrasting subjects were showed in Fig.2. Fig.2(a) is for a young healthy subject with evenly distributed histogram. Fig.2(b) is for a subject from Old group with a concentrated distribution. A more intensive centripetalism can be found in the distribution of subject from the CHF group in Fig.2(c). Data from Young, Old and CHF groups follows normal distributions (Kolmogorov-Smirnov test, p>0.05) and hemegeneous variance (test of Homogeneity of Variances in ANOVA, p<0.001). The boxplot shown in Fig. 3 present the statistical distribution of the cumulative density of the three groups. A more precise description of the cumulative density values can be found in Table 2. The subjects from the three groups performed an increased cumulative density, with mean values 0.0238 for Young, 0.0406 for Old, and 0.0732 for CHF. Results of ANOVA test with the Tamhane's T2 are showed in Table 2. Significant differences among the three groups can be found in Table 2 (p<0.001).

Reasons to this finding could be due to the balance between the functions of sympathetic and parasympathetic nervous systems that is controlled by the autonomic nervous system (ANS). A healthy balance between the sympathetic and parasympathetic nervous system produces an ongoing oscillation -- orderly increase and decrease in heart rate [1], [3]. But an abnormal balance can lead to a diminished variability that is usually associated with ageing and illnesses. The method advanced in this study enables to reflect the imbalances of HRV through the histogram. Therefore it is considered a valid method in assessment of HRV in the healthy and elderly subjects, as well as in the CHF patients.
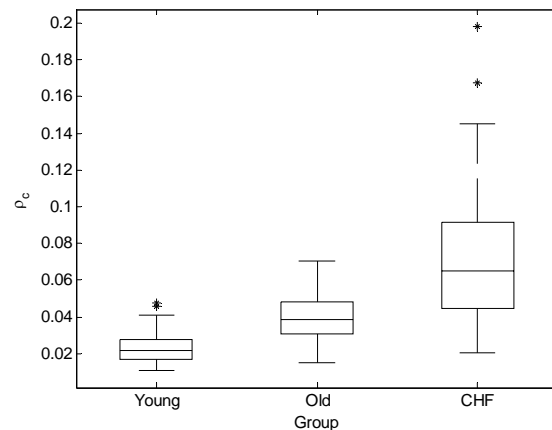

Fig. 3 Boxplot illustrating the cumulative density of the subjects in the three groups

TABLE II
CUMULATIVE DENSITY

	Young	Old	CHF	Multiple comparisons	F test
ρ_c	0.0238±0.0087	0.0406±0.0129	0.0732±0.0376	p <0.001 p <0.001 p <0.001	p <0.001

B. The Test-Retest Reliability

After 7 and 14 days, forty-six healthy subjects (20 females and 26 males, age: 43±16 y; height: 168±8cm; weight: 64±11kg; BMI: 22.5±3.0kg/m2) who participated in the first test were retested twice following the same test protocol in order to examine the test-retest reliability of the algorithm. Some heart routine indices were also examined, including the heart rate (67±8 beats/min); systolic blood pressure (106±12 mmHg); diastolic blood pressure (73±9 mmHg); and left ventricular ejection fraction (66±6%). All data were in normal ranges.

Kolmogorov-Smirnov test examined that all data in the three tests followed normal distributions (p>0.05). Test of Homogeneity of Variances showed homogeneous variance for all the three sequenced evaluations (p=0.918). Boxplot in Fig. 4 showed similar distribution of the cumulative density across the three evaluations. Detailed information about the three evaluations has been presented in Table 3. A good-to-excellent reliability can be found in the test-retest analysis, with an ICC=0.783 (95% CI: 0.676-0.864). This finding is reinforced in Fig. 5 by the Bland-Altman plots between each two evaluations, where average 95.7% points were within the 1.96 standard deviations (93.5% for the first-second evaluations, 95.7% for the first-third evaluations, and 97.8% for the second-third evaluations.)
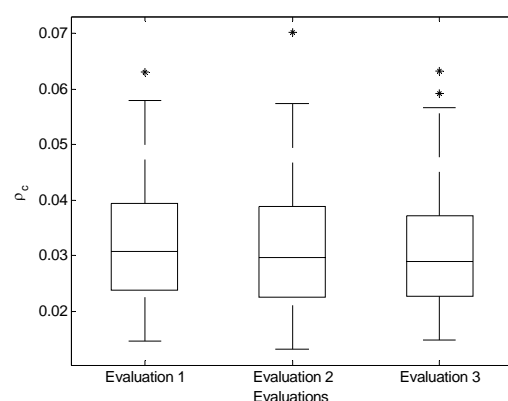

Fig. 4 Boxplot illustrating the cumulative density of the three evaluations for reliability

IV. CONCLUSION

This work examined the validity and reliability of a novel method – the five-class density histogram, in non-invasive assessment of HRV. The main result of this study is particularly important as the five-class density histogram it suggests is an effective, reliable and simple method that can be widely applied in HRV assessment, particularly for the short-term series. Further analyses in large healthy population as well as the patients with various cardiovascular diseases obviously need to be performed in order to support a wide use of five-class density histogram in analysis of short-term HRV.

TABLE III
ICC OF THE CUMULATIVE DENSITY ACROSS THREE EVALUATIONS

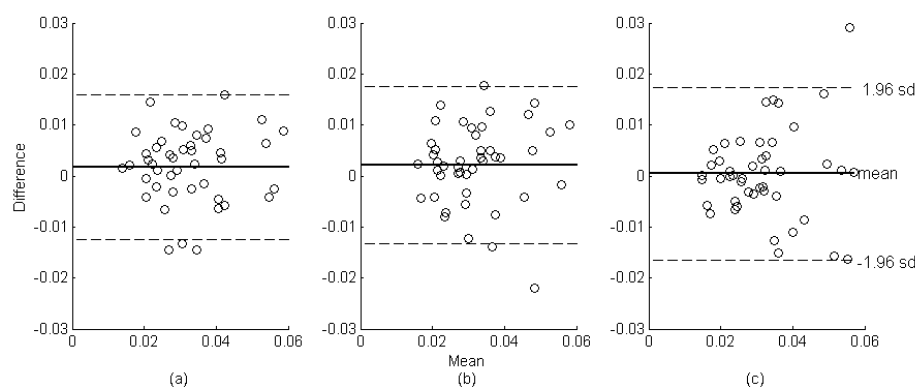|	Evaluation 1	Evaluation 2	Evaluation 3	ICC(95%CI)
ρ_c	0.034±0.012	0.032±0.013	0.032±0.012	0.783(0.676-0.864)

Fig. 5 Bland-Altman plots of intra-observer differences against the mean. (a) Results of the first and second evaluations. Mean: 0.0017; SD: 0.0072; mean+1.96SD=0.0158; mean-1.96SD=-0.0124. (b) Results of the first and third evaluations. Mean: 0.0021; SD: 0.0078; mean+1.96SD=0.0175; mean-1.96SD=-0.0132. (c) Results of the second and third evaluations. Mean: 0.0004; SD: 0.0086; mean+1.96SD=0.0174; mean-1.96SD=-0.0165. Dotted line represents 1.96 standard deviations from the mean values

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