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Ejection Fraction Measurement Based on Impedance Cardiography

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Abstract: Ejection fraction (EF) is an important indicator of cardiac function, especially in clinical conditions. Unlike imaging technology such as echocardiography, impedance cardiography (ICG) is a low-cost, non-invasive and continuous method of monitoring EF. However, the accuracy of the ICG method to evaluate the EF value needs to be further improved. This paper uses a simplified ventricular model to simplify the complex relationship between the EF value and the relevant ICG parameters, and proposes a method for calculating the EF value through these relevant ICG parameters. We tested this method with 52 subjects. Experimental results show that compared with the traditional ICG method, the proposed method has a higher correlation and closer agreement with the EF measurement by echocardiography. The proposed scheme effectively improves the reliability of the measurement of the EF value relying on the ICG signal.

1 INTRODUCTION

Heart failure (HF) is a serious heart disease that is associated with diminished cardiac function. It is mainly manifested as blood stasis in the ventricles, which cannot be fully ejected, and is usually characterized by abnormal hemodynamic (Murphy, 2020). The most common description of ventricular function in patients with HF is ejection fraction (EF) (Parrott, 2004). EF refers to the stroke volume as a percentage of the ventricular end-diastolic volume. When the ventricles contract, the blood in the ventricles cannot be injected into the arteries completely. Therefore, there is still a certain amount of residual blood in the ventricle when the ejection is completed. The EF is related to the contractility of the myocardium. The stronger the myocardial contractility, the greater the stroke volume and the greater the ejection fraction (Pucci, 2020).

Imaging technology is a common method for measuring EF, such as echocardiography. Echocardiography is a necessary method to determine the diagnosis of HF and highly recommended if HF is suspected (Kaszuba, 2013). However, it is time-consuming and expensive, and the measurement results are discontinuous and moderately subjective (Lai, 2020). Therefore, complicated measurements are impractical in the clinical management of HF patients. In contrast, impedance cardiography (ICG) is a simple, low-cost, non-invasive and continuous hemodynamic monitoring method, and it is a recognized technique for evaluating cardiac function (Anand, 2021). It monitors the thoracic impedance and correlates impedance variation with various events in the cardiac cycle, which has high reproducibility and is closely related to invasive measures such as thermodilution using pulmonary artery catheters (Albert, 2004). The ICG injects a high-frequency low-amplitude constant current into the thorax through two electrodes. Another pair of electrodes placed on the boundary of the current injecting electrodes are used to measure the thoracic voltage. Finally, the time-varying impedance signal is obtained through Ohm's law, and the negative of the impedance derivative is called the ICG (Bagal, 2017).

Although the ICG method for measuring stroke volume (SV) and cardiac output (CO) has been clinically recognized, the accuracy of the ICG method for evaluating EF values needs to be further improved (Hugh, 1994; Van der Meer NJ, 1996; Thompson, 2008). Considering the relationship between the change in left ventricular volume during ejection period and the physiological parameters measured by simultaneously collected ICG, this paper uses a simplified ventricular model to simplify the complex relationship between the EF value and the relevant ICG parameters, and proposes a method for calculating the EF value through these relevant ICG parameters. We tested this method with 52 subjects and compared the EF measured by the proposed method with the existing ICG method. The experimental results show that compared with the existing ICG method, the proposed method has a higher correlation and closer agreement with the EF measurement by echocardiography. The paper is organized as follows. Section II introduces the proposed method. The experimental results and the discussion are presented in Section III and IV, respectively. We conclude the paper in Section V.

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2 METHODS

2.1 Dataset

The ICG signal was obtained through a physiological signal module Enduro (Physioflow). According to the description of Kubicek et al., the ICG signal is obtained by a classic tetrapolar array (Kubicek, 1974). Before the experiment, the height, weight, and blood pressure of the subjects were measured, and then use Enduro to collecte the heart rate (HR), stroke volume (SV), contractility Index (CTI, from the description of PhysioFlow_User_Manual Operating Instructions 2009, CTI is equal to dZ/dt_{max}, and dZ/dt_{max} is maximum of ICG in a cardiac cycle), and left ventricular ejection time (LVET). Pre-ejection period (PEP) and CTI/dZ_{tot} were acquired through the waveform recorded by Enduro, dZ_{tot} is total change of the ICG from presystolic minimum to midsystolic maximum.

Each subject first lay on the bed, measured the ICG related parameters after resting, and then measured the EF value by echocardiography. There were 52 subjects (28 female, 24 male) with an age range from 30 to 90 years. Figure 1 is the ICG and echocardiographic measurement scenarios. The experimental procedures were approved by the Ethics Committee in Human Research of the University of Science and Technology of China. All the volunteers filled out an informed consent form before collection the data.

Figure 1. ICG and echocardiographic measurement scenarios.

2.2 EF study

The definition of EF value is (EDV-ESV)/EDV, where EDV is end-diastolic volume and ESV is endsystolic volume. Because stroke volume (SV) is equal to EDV - ESV, the formula can be rewritten as:

$$EF = SV/EDV \tag{1}$$

Assuming that the human ventricle is in the shape of a sphere, the radii of diastole and systole of the ventricle are set to r_1 and r_2, respectively, as shown in Figure 2. Then, the SV is expressed as shown in formula 2,

$$SV = \frac{4\pi r_1^3}{3} - \frac{4\pi r_2^3}{3} \tag{2}$$

For a certain cardiomyocyte of the ventricle, it moves from point A to point B during the diastole to systole. We set the distance between A and B to r_m,

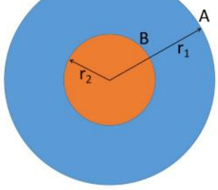


Figure 2. Simplified ventricular model.

$$r_m = r_1 - r_2 \tag{3}$$

Through formulas 1 and 2, we get the value of r_1 as shown in formula 4,

$$r_1 = \frac{r_m}{2} + \sqrt{\frac{SV}{\pi r_m} - \frac{1}{12} r_m^2} \tag{4}$$

The EF value of a person is generally between 30% to 70%. For EF < 50%, we get $r_m < 0.2r_1$, $r_m^2/12 < 0.01r_1^2$, so these parts can be ignored, and we can get,

$$r_1 \approx \sqrt{\frac{SV}{\pi r_m}} \tag{5}$$

For 50% < EF < 70%, we get $0.2r_1 < r_m < 0.34r_1$, $\sqrt{\frac{SV}{\pi r_m}} > 0.83r_1$, in order to simplify the calculation, we use the formula 6 to express r_1,

$$r_1 = k_1 \sqrt{\frac{SV}{4\pi r_m}} \tag{6}$$

where k_1 is a constant. Considering that r_m is the displacement of myocardial cells during a heart beat, the displacement time is equal to the ejection time LVET, and the acceleration of the displacement is related to the heart contraction index CTI (expressed as dZ/dt_{max} in ICG). Considering that the pre-ejection period (PEP) value will increase when the myocardial contraction is weak (Etemadi, 2009), and finally we used formula 6 to express r_m,

$$r_m = \frac{1}{2}\frac{F}{m_0} t_e^2 = \frac{1}{2}\frac{dZ/dt_{max}}{PEP} LVET^2 \tag{7}$$

where F is average myocardial contraction force, m_0 is the mass of cardiomyocytes, t_e is the ejection time, equal to LVET. Considering that the product of dZ/dt_{max} and LVET is proportional to the SV (KUBICEK, 1966; Nazário, 2017), we use the following formula 8 to express r_m,

$$r_m = k_2 SV \frac{LVET}{PEP} \tag{8}$$

where k_2 is a constant. According to the definition of EF, EF can be expressed by the formula 9,

$$EF = SV/\frac{4\pi r_1^3}{3} = k_3\sqrt{\frac{r_m^3}{SV}} = k_4 SV(LVET/PEP)^{3/2} \quad (9)$$

where k_3, k_4 are constants. Considering that the SV of the subjects with heavy height and body weight will be higher, but the EF value of these subjects are usually normal, To avoid this problem, we use stroke volume index (SVi) instead of SV. SVi is equal to SV/BSA, so EF can be expressed by the formula 10,

$$EF \propto SV/BSA(LVET/PEP)^{3/2} \quad (10)$$

where BSA is body surface area and can be calculated by height and weight.

2.3 Existing ICG method of measuring EF

Although ICG is mainly used to measure SV and CO, many researchers also use it to measure EF. Cap et al. used PEP/LVET to characterize EF, and found that the EF value is negatively correlated with PEP/LVET (Capan, 1987). Jud et al. proposed to use the ratio of dZ/dt_{max} and dZ_{tot} to characterize EF (Judy, 1983), and found that the EF value is positively correlated with $dZ/dt_{max}/dZ_{tot}$. Nardo et al. did further research on the basis of Jud's method, found that $dZ/dt_{max}/dZ_{tot}LVET$ and $dZ/dt_{max}/dZ_{tot}/HR$ have stronger correlation coefficients with the real EF value. This article also analyzes the results of these existing ICG techniques to measure EF (Van der Meer, 1996).

3 RESULTS

3.1 Raw data

As shown in Table I, the EF, height, weight, CTI, PEP, LVET, CTI/dZ_{tot} and SV values of 52 subjects were recorded. The subjects were divided into 5 groups based on the subjects' EF_{Echo} value. 17 subjects had EF ≥ 65%, 11 subjects between 60% and 65%, 11 subjects between 50% and 60%, and 10 subjects between 40% and 50%, 3 of these had an EF below 40%. At the same time, the average value and standard deviation of height and weight in the subgrouping are recorded separately, and the specific parameters can be seen in Table 1.

Table 1 Raw data classification and its mean and standard deviation.

	EF ≥ 65% (n=17)	60% ≤ EF < 65% (n=11)	50% ≤ EF < 60% (n=11)	40% ≤ EF < 50% (n=10)	EF < 40% (n=3)
H	164.3±8.0	162.3±6.1	167.3±4.5	166.0±5.4	170.3±2.0
W	63.9±11.9	66.0±7.7	73.4±9.7	71.5±7.8	74.0±8.6

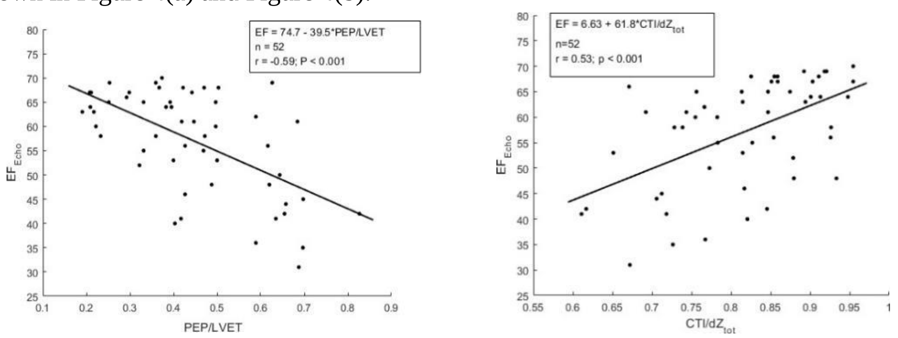
3.2 Existing ICG methods

As mentioned earlier, many researchers use ICG to measure EF. Cap et al. proposed that the EF value is negatively correlated with PEP/LVET, as shown in Figure 3(a), the correlation coefficient r between EF and PEP/LVET is -0.59, p < 0.001, therefore, there is a certain correlation between the them. Jud et al. consider that EF has a certain correlation with CTI/dZ_{tot}, Figure 3(b) draws a scatter diagram of between EF and CTI/dZ_{tot}, and calculate the correlation coefficient r equal to 0.53, p < 0.001, which also shows that the two have a certain correlation. Imp1 and Imp2 are improved methods based on Jud, and the correlation with EF is 0.55 and 0.61 respectively, as shown in Figure 4(a) and Figure 4(b).

3.3 The proposed method

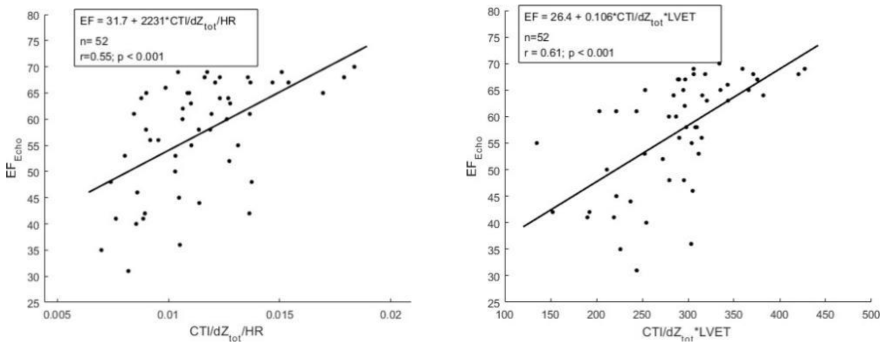
Figure 5 shows that the correlation coefficient between EF and $SV/BSA/(LVET/PEP)^{1.5}$ is as high as 0.81, and the p < 0.001, indicating that they have a stronger correlation compared with existing ICG methods.

From the Figure 6, the Bland-Altman diagram also shows that, the EF value measured by proposed method is in close agreement with that measured by echocardiographic. There is only one subject parameter outside of mean+1.96σ, with an average error of -0.01 and a standard deviation of 6.0, indicating the effectiveness of the method.



(a) (b)

Figure 3. Correlation between EF_{Echo}, PEP/LVET and CTI/dZ_{tot}.



(a) (b)

Figure 4. Correlation between $\mathrm{EF_{Echo}}$, $CTI/dZ_{tot}HR$ and $CTI/dZ_{tot}LVET$.

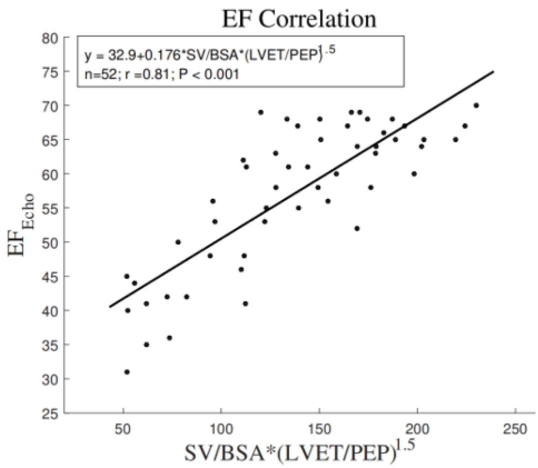


Figure 5. Correlation between $\mathrm{EF_{Echo}}$and $\mathrm{SV/BSA/(LVET/PEP)^{1.5}}$.

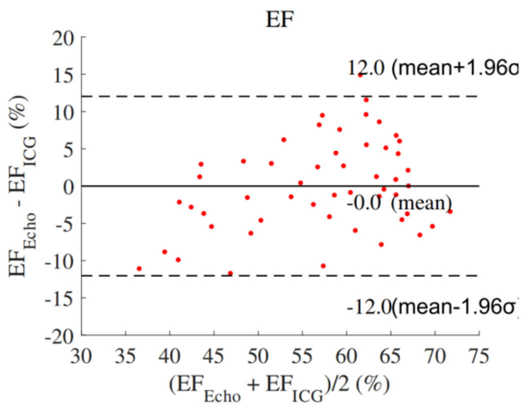


Figure 6. Bland-Altman diagram between $\mathrm{EF_{Echo}}$ and $\mathrm{EF_{ICG}}$.

4 DISCUSSION

There is no doubt that ICG has considerable value in clinical and scientific, especially in tracking the relative changes in CO. But for doctors interested in heart failure, the measurement of EF is undoubtedly more important clinically than the measurement of CO (Beitzke, 2002). However, because it is difficult to determine the end-diastolic left ventricular volume, the EF value measured by ICG has not been clinically recognized.

Table 2 Mean EF (+ SD) calculated according to the equations and their Correlation to EF.

Method	Mean EF	R	Regression Line	mean±sd
Cap	57.05±6.24	0.59	Y = 74.7 - 39.5*X	- 0.05 ± 11.5
Jud	57.08±5.58	0.53	Y = 6.63 + 61.8*X	-0.02 ± 12.8
Imp1	57.07±5.74	0.55	Y = 31.7 + 2231*X	-0.03 ± 10.2
Imp2	56.96±6.41	0.61	Y = 26.4 + 0.106*X	-0.10 ± 8.4
This study	57.09±8.52	0.81	Y = 32.9 + 0.176*X	-0.01 ± 6.0

Several existing EF calculation methods by ICG have also been included in our study, as shown in Table II. The results show that the existing ICG methods have a low correlation with $\mathrm{EF_{Echo}}$ and are not suitable for determining EF, which confirms the results of Bowling et al. in patients with heart failure (Bowling, 1993). In this paper, uses a simplified ventricular model to simplify the complex relationship between the EF value and the relevant ICG parameters, and proposes a method for calculating the EF value through these relevant ICG parameters. In order to prove that the proposed method can prospectively provide EF prediction for patients with unknown cardiac function, 52 patients subjects with vascular diseases are tested. The correlation coefficient between $\mathrm{SV/BSA/(LVET/PEP)^{1.5}}$ and $\mathrm{EF_{Echo}}$ reached 0.81, indicating the effectiveness of the proposed method. The correlation between $\mathrm{EF_{Echo}}$ and $\mathrm{EF_{ICG}}$, especially the Bland Altman diagram, shown in Figure 5, gives us reason to hope that in the future, compared with time-consuming echocardiographic measurements, the ICG method to measure EF would be highly desirable.

In summarise, this study shows that the proposed method has great significance for the improvement of the accuracy of ICG's assessment of EF. Although these measurement methods will certainly not replace echocardiography, in view of the prevalence of HF, especially in countries with increasing aging, this method is still very important for general treatment.

5 CONCLUSION

In this paper, we uses a simplified ventricular model to simplify the complex relationship between the EF value and the relevant ICG parameters, and proposes a method for calculating the EF value through these relevant ICG parameters. In order to prove the effectiveness of the proposed method, 52 subjects with cardiovascular diseases were tested. The results show that the EF value measured by this method is in good agreement with the EF value measured by echocardiography, thereby improving the reliability of the EF measured by the ICG method.

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