



Study on Self-Monitoring Method of Ankle Impedance

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Abstract

Objective The aim of the study was to analyze the self-monitoring ankle impedance measuring instrument for patients with heart failure and to evaluate the degree of ankle impedance variation in normal young people for three days.

Methods We developed a portable impedance measuring instrument based on AD5940 chip of ADI. The circuit composed of programmable alternating current (AC) voltage generator, digital signal processor, microcontroller, and related peripheral circuits. The four-line body impedance analysis measurement method was used, which was powered by two 1.5-V batteries, and a frequency of 50 kHz was selected to improve the measurement accuracy. The bioimpedance of the human body can be measured in the range of 0 to 2,000 Ω , and the phase range is -180 to $+180$ degrees, both of which are accurate to two decimal places. Ten normal young volunteers were included, with an average age of 24.5 ± 1.3 years. The electrical impedance of the right ankle was measured in the sitting position, the supine position, and the standing position. Each posture was measured three times, and the variation of the ankle impedance was observed for three days at the same time point.

Results There was no significant difference in ankle impedance between the three positions of 10 volunteers in this group during the three days. The mean difference between the mean groups ranged from 6.14 to 9.53%, and the maximum difference was 9.53%. There was no significant correlation between ankle impedance and BMI in the three positions.

Conclusion Although there are some changes in the ankle impedance measured by the self-developed impedance tester within three days, it can still monitor the ankle impedance of normal young people relatively stably. This impedance meter may be used for home monitoring of ankle impedance in patients with heart failure.

Keywords

- ▶ body electrical impedance
- ▶ ankle
- ▶ body position
- ▶ heart failure

Introduction

Electrical bioimpedance technology is a noninvasive detection technology that uses the electrical characteristics and changes of biological tissues and organs to extract relevant information.^{1,2} Its advantages are noninvasive, low cost, and safety. At present, the electrical impedance method has been widely used in the monitoring of respiratory, cardiac, and gastric dynamics.³⁻⁵

For patients with heart failure, especially those with right heart failure, the degree of lower extremity edema has been considered an important indicator for assessing disease changes.^{6,7} Studies have shown that in the general population, lower limb impedance is negatively correlated with the incidence of heart failure.⁸ Since the resistance of water is lower than that of muscle, fat, or bone,⁹ ankle edema will lead to a decrease in ankle impedance, and after the edema subsides, the ankle impedance returns to its original level. Therefore, the

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an analog-to-digital converter (ADC). The digital signal processor performs accurate digital signal measurement.^{20,21}

In ► **Fig. 1**, to ensure that the whole body is not affected by direct current (DC) voltage, discrete isolation capacitors (C_{ISO1} , C_{ISO2} , C_{ISO3} , and C_{ISO4}) are used, each of which is 0.47 μF . To meet the requirements of IEC 60601 standard,²² the current limiter R_{LIMIT} with a current of 1 k Ω provided to the sensor is limited, ensuring that the maximum DC current allowed to enter the body is 10 μA . During the measurement, the excitation current frequency is set to 50 kHz, 500 μA .

Bioimpedance is a complex number composed of resistance value R (real part) and reactance value X_c (imaginary part). The resistance value R mainly reflects the degree of obstruction of the total amount of water in the human body to the current, while the reactance value X_c mainly reflects the ability of the capacitance to response generated by the cell membrane to the current.^{10,23,24} The formula of biological impedance Z is the following:

$$Z = R + jX_c \quad (1)$$

The portable impedance meter outputs two values by default: impedance ($|Z|$) and phase (θ). In this experiment, Ohm's law is used to calculate the impedance, that is, the voltage amplitude ($|U|$, representing the maximum amplitude of the voltage signal) is divided by the current amplitude ($|I|$, representing the maximum positive amplitude in the current signal). To convert the current measurement into a voltage, the gain resistance of the high-speed TIA R_{TIA} (set to 1 k Ω in this experiment) is used. In the calculation formula of impedance, this gain factor is considered:

$$|Z| = \frac{|U|}{|I|} \times R_{TIA} \quad (2)$$

In patients with heart failure, fluid retention is common in the lungs and lower extremities. Real impedance can effectively analyze and evaluate lower extremity edema. The impedance can be expressed by the vector of the modulus $|Z|$ and the phase angle θ . The following is the determination formula of real part impedance and phase angle θ :

$$\text{Real part impedance} = |Z| \cos \theta \quad (3)$$

$$\theta = \tan^{-1} \frac{X_c}{R} \quad (4)$$

The portable impedance measuring instrument can measure the biological impedance range of human body from 0 to 2,000 Ω , the phase range from -180 to $+180$ degrees, and provide the measurement accuracy of two decimal places.

Verification of Portable Ankle Impedance Measuring Instrument

The participants were 10 young college volunteers. The mean age was 23.9 ± 1.7 years. Their age, height, weight, and body mass index (BMI) were recorded, and no history of disease was recorded. Using the portable impedance measuring instrument, using the four-line body impedance analysis

(BIA) measurement method, the electrical impedance of the right ankle was measured at three different positions: for three minutes in the sitting position, for five minutes in the supine position, and for three minutes in standing position. Each position was measured three times, measured continuously at the same time point every day for three consecutive days. There was no significant change in the law of life and movement of all subjects during the test period.

Impedance Measurement Electrode Placement

Four button electrodes were placed on the left and right sides of 2 to 3 cm above the right ankle, two on each side, with positive and negative poles corresponding to each other. The corresponding wires were connected to measure the impedance of the right ankle. During each measurement, the ankle impedance of the three postures was measured according to the order of sitting, lying, and standing positions, and the electrode was retained in the original position (the electrode placement position is shown in ► **Fig. 1**).

- Sitting position: feet flat on the ground after three minutes.
- Lying position: after lying flat for five minutes.
- Standing position: feet together, standing for three minutes.
- Ankle impedance: data that reach a stable state during instrument monitoring.
- Impedance difference: the difference between the maximum and minimum values of the same position for three days (Ω).

Impedance difference = impedance difference / three -day average impedance (%).

Statistical Methods

Statistical analysis was performed using GraphPad Prism 9.5 software. All the sampling data were repeated three times, and the measurement data with normal distribution were expressed as mean \pm standard deviation ($x \pm s$). Paired sample t -test was used for comparison between the two groups. More than two groups were compared using the Geisser-Greenhouse corrected analysis of variance. Tukey's multiple comparisons were used for postanalysis. Pearson's correlation coefficient was calculated for correlation analysis. A p value less than 0.05 was considered statistically significant.

Result

In our experiment, the general information collected from the volunteers included height, weight, BMI, and age. The specific values were as follows:

Height: The average height was 1.75 m, with a standard deviation of 0.055 m.

Weight: The average weight was 68.7 kg, with a standard deviation of 9.473 kg.

BMI: The average BMI was 22.52, with a standard deviation of 2.946, measured in kilograms per square meter.

Age: The average age was 23.9 years, with a standard deviation of 1.729 years.

Table 1 Electrical impedance (Ω) and its difference (%) of the real part of the ankle in the sitting position of 10 participants every day

Participant number	Ankle real part impedance (Ω)			Difference (Ω)	Average impedance (Ω)	Difference degree
	Day1	Day 2	Day 3			
1	22.64	20.23	22.92	2.69	21.93	12.26%
2	23.56	24.30	20.49	3.80	22.78	16.69%
3	20.64	22.42	20.56	1.87	21.21	8.81%
4	19.00	21.37	21.05	2.37	20.47	11.56%
5	17.42	23.79	23.38	6.37	21.53	29.60%
6	21.03	19.81	25.72	5.91	22.18	26.64%
7	18.77	25.88	20.10	7.11	21.58	32.94%
8	28.80	32.60	27.47	5.14	29.62	17.34%
9	18.19	17.45	17.22	0.97	17.62	5.52%
10	17.77	20.04	18.99	2.26	18.93	11.94%
All	20.78 \pm 3.49	22.79 \pm 4.25	21.79 \pm 3.11	6.14	21.79	28.18%

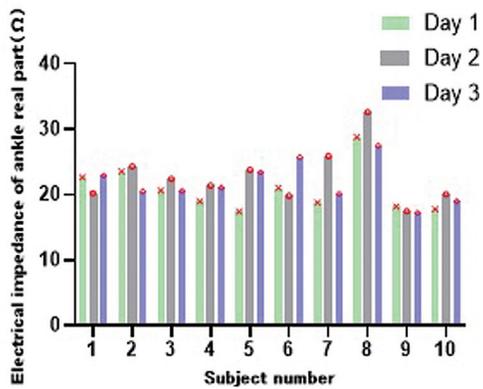


Fig. 2 The real impedance in the sitting position of 10 subjects in 3 days.

As a group, the average value of the real part impedance of the sitting ankle of the 10 participants during the three days is shown in **Table 1**, and the real part impedance value is the average value of the real part impedance in the sitting position during the day. The interindividual difference was between 17.2 and 32.6 Ω , and the intraindividual difference of ankle real

impedance was between 0.97 and 7.11 Ω . The difference was 5.52 to 32.94%. The change of the real part impedance of the sitting position in three days is shown in **Fig. 2**.

Table 2 shows the average real impedance of different positions in three days. The impedance values of the real part of the ankle between the sitting, lying, and standing positions during the three days were very close, and there was no significant difference. The intragroup difference of the sitting position was 9.53%, that of the lying position was 6.60%, and that of the standing position was 6.14% (**Table 2**).

Fig. 3 shows the ankle electrical impedance of the participants in different positions within three days. Ankle real impedance for the first day of standing and sitting was similar; the standing ankle real impedance for the other 2 days were significantly lower than the sitting position impedance; at the same time, the real impedance of the supine position for three days was also significantly lower than that of the sitting position.

As shown in **Fig. 4**, according to the impedance data on the first day, the correlation between impedance and BMI in different positions was analyzed. It was found that the real part impedances of the sitting position ($r = -0.02281$,

Table 2 The changes of average ankle real part impedance in the sitting, lying, and standing positions during 3 days

	Sitting impedance (Ω)	Standing impedance (Ω)	Lying position (Ω)	Difference (Ω)	Difference degree
Total	21.79 \pm 3.62	21.32 \pm 3.26	20.47 \pm 3.31	/	/
Day 1	20.78 \pm 3.49	20.77 \pm 3.06	19.93 \pm 3.00	0.85	4.15%
Day 2	22.79 \pm 4.25	22.08 \pm 3.69	21.28 \pm 4.09	1.51	6.84%
Day 3	21.79 \pm 3.11	21.13 \pm 3.19	20.20 \pm 2.89	1.59	7.56%
Mean difference	2.01	1.31	1.35	/	/
Mean difference degree	9.53%	6.14%	6.60%	/	/

* $p < 0.05$.
** $p < 0.01$.

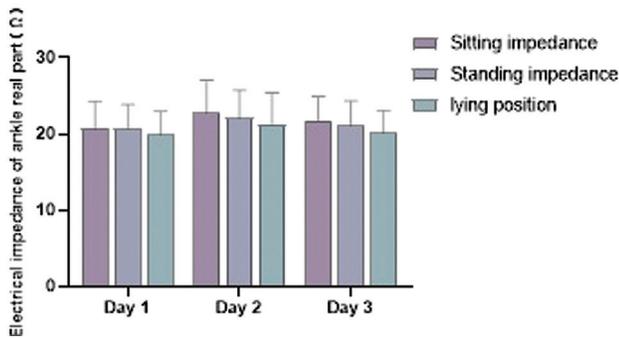


Fig. 3 The impedance of the real part of the ankle in different positions in 3 days.

$p = 0.9501$), standing position ($r = 0.02739$, $p = 0.9401$), and lying position ($r = 0.1467$, $p = 0.6860$) were not significantly correlated with BMI.

Discussion

Using a bioimpedance spectroscopy device, it is possible to noninvasively obtain various volume load information, including overhydration (OH) and overhydration/extracellular water (OH/ECW%), which can predict cardiovascular events (CVEs). The single-frequency bioimpedance instrument presented in this study is lightweight, weighing only 200 g, and compact in size ($7 \times 12 \times 4$ cm), with easy operation. It has demonstrated the ability to provide stable and reliable ankle impedance data in healthy and young individuals.

Preliminary research results indicate a significant negative correlation between leg bioimpedance and heart failure, a finding that holds true even after controlling for age and gender. In a 9.8-year follow-up study, we found hazard ratios (95% confidence intervals) of 0.60 (0.48–0.73) and 0.75 (0.59–0.94), respectively, indicating good discrimination ([C-index] = 0.82) and calibration performance.⁸ These findings further confirm the potential application of ankle impedance measurement in assessing the fluid status of patients, especially those with heart failure.

To establish standards for edema measurement, we first conducted validation in healthy and young individuals.

We found certain differences in the real part of ankle impedance under different postures, with a difference of 9.52% in the sitting position, 6.60% in the supine position, and 6.14% in the upright position. Among the 10 young participants, the real part impedance value of the ankle in the sitting position ranged from 17.2 to 32.6 Ω , with individual differences. The difference over three days ranged from 5.52 to 32.94%. These data emphasize the importance of considering individual differences and posture-related factors in actual measurements. Our study also found that the real part of ankle impedance in the sitting position has good stability on different days, which may be related to the consistency of monitoring operations. Therefore, when using the real part of ankle impedance as a monitoring tool, ensuring the consistency and accuracy of operations is crucial for the reliability of the results.

Based on these findings, we suggest that the real part of ankle impedance can serve as an effective tool for monitoring body volume load. On the same day, we observed that the real part of ankle impedance in the standing and supine positions was lower than that in the sitting position, and the real part impedance in the supine position was also lower than that in the standing position. This indicates that posture changes can lead to significant changes in ankle impedance (6.14%–9.52%). Muscle strength and the state of blood reflux may be related to changes in ankle impedance with posture changes. For example, when standing, the hydrostatic pressure in the arteries and veins of the lower limbs increases, affecting blood return, thus reducing the real part of ankle impedance.²⁵ Therefore, when monitoring ankle impedance at home, the same posture should be maintained to reduce errors caused by posture changes and ensure data accuracy. From the perspective of ease of use, the sitting position is not only more comfortable but also more convenient.

Furthermore, we found no significant correlation between the real impedance of the ankle and BMI in the three postures, indicating that BMI is not an important factor affecting the real impedance of the ankle.

Our novel bioimpedance measurement device provides a new tool for home monitoring, with preliminary validation

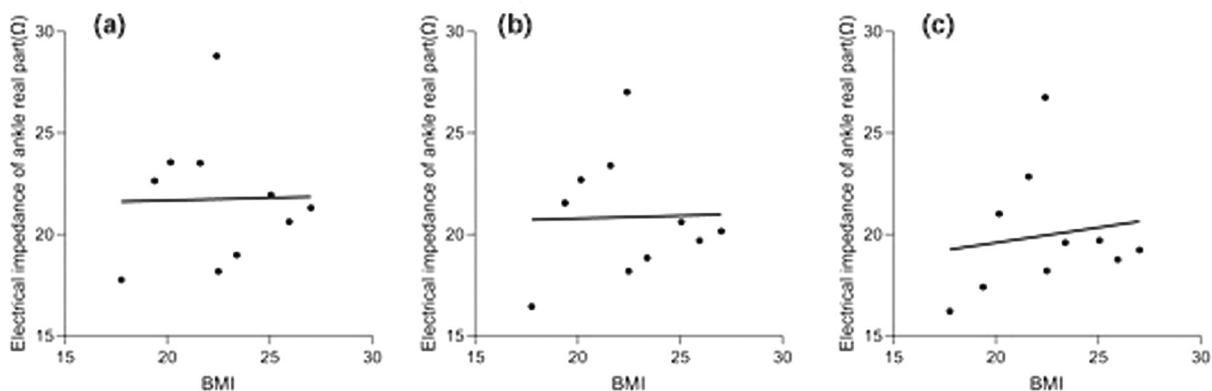


Fig. 4 Correlation analysis of ankle impedance and body mass index (BMI) in three positions. (a) Sitting. (b) Standing. (c) Lying.

confirming its effectiveness in healthy and young individuals. Our current research focus is on establishing and validating impedance measurement standards in healthy and young individuals. We chose to first validate in young individuals because the pathological state in heart failure patients is more complex and requires more in-depth research. At the same time, we are also conducting related research in heart failure patients to explore the potential application of our device in this specific population. Our goal is to first establish edema measurement standards in young individuals and then gradually extend to heart failure patients, with the aim of providing a more comprehensive health management plan for patients. We are currently conducting simultaneous measurement experiments in heart failure patients, which will provide us with valuable data to better understand the performance and application potential of the device under different pathological conditions.

Although our preliminary validation indicates that the device performs well in a small sample, to enhance the reliability and universality of the research, future studies need to be conducted in a larger population of heart failure patients.

Conclusions

In this study, a household bioelectrical impedance analyzer with AD5940 as the measurement unit was presented. The four-line BIA measurement method was used to measure the ankle impedance of 10 normal young volunteers for three consecutive days. It was found that the impedance values of the real part of the ankle between the sitting, lying, and standing positions during the three days were very close, and there was no significant difference. There was no significant correlation between the impedance of the ankle and BMI in different positions. The real part of the ankle impedance data of the same individual for three days is basically stable. Because of its small size and simple operation, the instrument has the application value of family monitoring of ankle impedance in patients with heart failure.

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Conflict of Interest

None declared.

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