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Original Article

# 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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change of ankle impedance can reflect the change of lower extremity edema, which is of clinical significance in evaluating the condition of patients with right heart failure.[10,11]

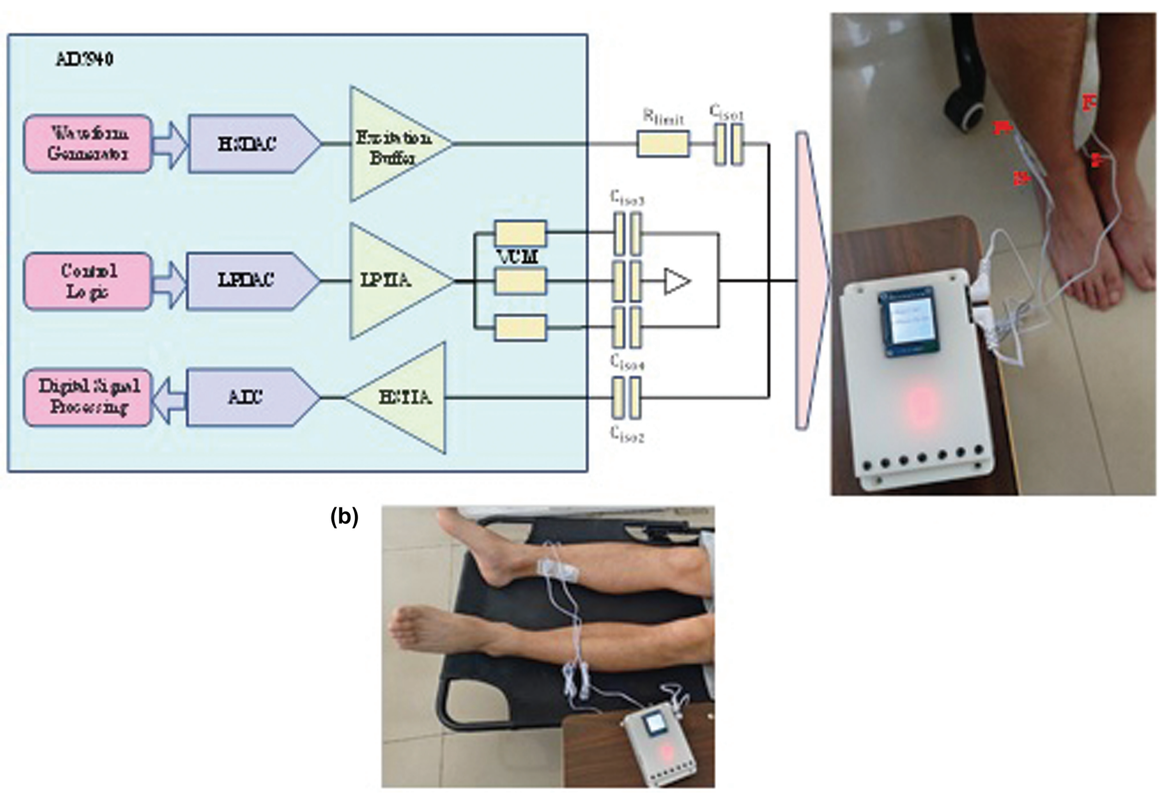
At present, the bioimpedance measuring instruments on the market are expensive and have complex parameters, which require professional operation and maintenance, and are not suitable for patients to monitor themselves at home. Although the latest small impedance measurement equipment has been studied, it is not specifically for home self-monitoring of patients with heart failure. For example, the wearable impedance instrument developed by Mabrouk et al showed high accuracy and stability in assessing ankle edema, but required simultaneous measurement of two joints, increasing the complexity of hardware design and requiring professional guidance.[12] In the study by Muñoz et al,[13] they proposed a two-dimensional bioimpedance distribution estimation system based on the AD5933 impedance converter for precise impedance measurement. Although the study emphasized the characteristics of low cost and portability, our analysis indicates that the hardware cost of the device is $80.5, and the use of the system requires a certain level of technical knowledge, which limits its widespread adoption among nonprofessional user groups. For patients within a family who require self-monitoring, there may be a need for simpler, cost-effective, and easy-to-operate alternatives. To this end, we have developed a single-frequency, portable impedance measurement device. This instrument is designed to enable heart failure patients to conduct self-monitoring at home. By tracking changes in ankle impedance, it can help detect early signs of increased volume load, allowing for timely intervention. This approach aims to reduce the number of medical visits and improve patient outcomes.

Because the ankle electrical impedance may fluctuate in different positions and different days,[9,14,15] this study verified the stability of the instrument through normal young people. We verified the changes of the ankle impedance of the instrument in different positions and for three consecutive days to determine the degree of change in the ankle impedance of normal people. At the same time, we verified the effectiveness and feasibility of this portable instrument in home self-monitoring of patients with heart failure.

## Development of Portable Ankle Impedance Measuring Instrument

The portable ankle impedance measuring instrument uses ADI's AD5940 chip and four-line bioelectrical impedance analysis (BIA) measurement method.[12,16–18] The circuit includes a programmable alternating current (AC) voltage generator, a digital signal processor, a microcontroller main component, and a peripheral circuit, as shown in ►**Fig. 1**. The programmable AC voltage generator is responsible for generating AC signals and outputting excitation voltage to the electrode through a digital-to-analog converter (DAC) and a signal excitation driver. The microcontroller uses a low-power DAC and a low-power transimpedance amplifier (TIA) to output an accurate common-mode voltage (VCM).[19] After the excitation signal passes through the human body, the current is converted into a voltage through a cross-group amplifier (TIA), and then converted into a digital signal through

(a)




(b)

**Fig. 1** (**a**) The composition and connection of the four-wire bioimpedance circuit. (**b**) Ankle impedance measurement in the supine position.

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 kΩ 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:

$$Z = R + j\,X_c \quad (1)$$

The portable impedance meter outputs two values by default: impedance ($|Z|$) and phase ($\theta$). 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 kΩ 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 $\theta$. The following is the determination formula of real part impedance and phase angle $\theta$:

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

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

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 ± standard deviation (x ± 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 ± 3.49 | 22.79 ± 4.25 | 21.79 ± 3.11 | 6.14 | 21.79 | 28.18% |

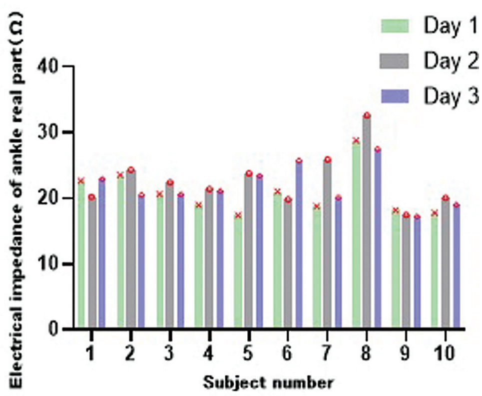



**Fig. 2** The real impedance in the sitting position of 10 subjects in 3 days.

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 ± 3.62 | 21.32 ± 3.26 | 20.47 ± 3.31 | / | / |
| Day 1 | 20.78 ± 3.49 | 20.77 ± 3.06 | 19.93 ± 3.00 | 0.85 | 4.15% |
| Day 2 | 22.79 ± 4.25 | 22.08 ± 3.69 | 21.28 ± 4.09 | 1.51 | 6.84% |
| Day 3 | 21.79 ± 3.11 | 21.13 ± 3.19 | 20.20 ± 2.89 | 1.59 | 7.56% |
| Mean difference | 2.01 | 1.31 | 1.35 | / | / |
| Mean difference degree | 9.53% | 6.14% | 6.60% | / | / |

$^{*}p < 0.05$.
$^{**}p < 0.01$.

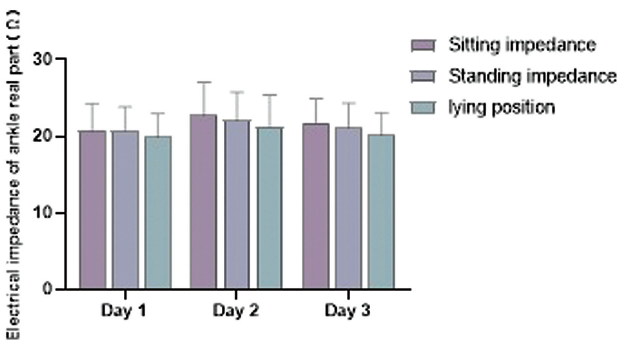



**Fig. 3** The impedance of the real part of the ankle in different positions in 3 days.

$p = 0.9501$), 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 × 12 × 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

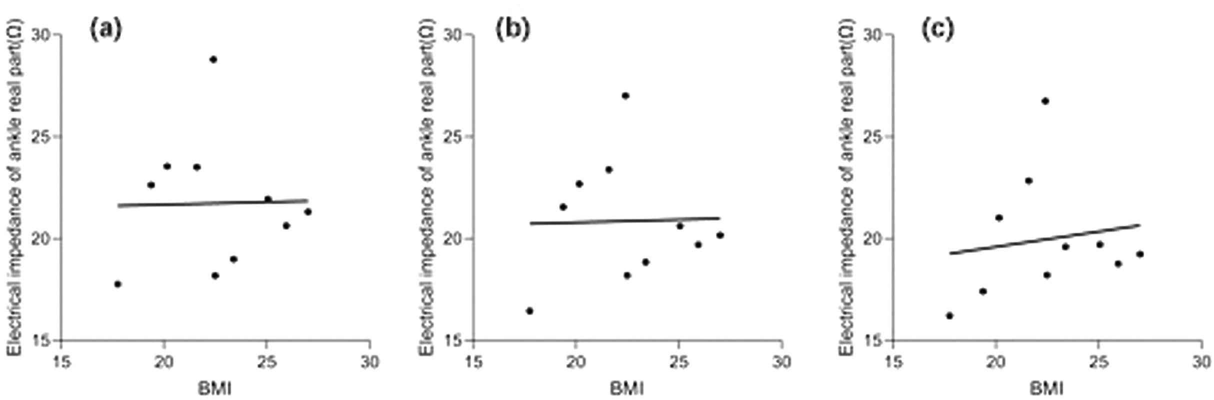



**Fig. 4** Correlation analysis of ankle impedance and body mass index (BMI) in three positions. (**a**) Sitting. (**b**) Standing. (**c**) Lying.

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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## References

1 Jethe JV, Deshpande AK, Ananthakrishnan TS, et al. Bioelectrical impedance analysis and its clinical application. MGM J Med Sci 2019;6:42–47

2 Stupin DD, Kuzina EA, Abelit AA, et al. Bioimpedance spectroscopy: basics and applications. ACS Biomater Sci Eng 2021;7(06):1962–1986

3 Cannon T, Choi J. Development of a segmental bioelectrical impedance spectroscopy device for body composition measurement. Sensors (Basel) 2019;19(22):4825

4 Zheng K, Lu J, Liu X, et al. The clinical application value of the extracellular-water-to-total-body-water ratio obtained by bioelectrical impedance analysis in people with advanced cancer. Nutrition 2022;96:111567

5 Küçükkubaş N, Aytar SH, Açıkada C, et al. Bioelectric impedance analyses for young male athletes: a validation study. Isokinet Exerc Sci 2020;28(01):49–58

6 Alnuwaysir RIS, Hoes MF, van Veldhuisen DJ, van der Meer P, Grote Beverborg N. Iron deficiency in heart failure: mechanisms and pathophysiology. J Clin Med 2021;11(01):125

7 Omar HR, Guglin M. Extent of jugular venous distension and lower extremity edema are the best tools from history and physical examination to identify heart failure exacerbation. Herz 2018;43 (08):752–758

8 Lindholm D, Fukaya E, Leeper NJ, Ingelsson E. Bioimpedance and new-onset heart failure: a longitudinal study of> 500 000 individuals from the general population. J Am Heart Assoc 2018;7 (13):e008970

9 Jaffrin MY, Morel H. Body fluid volumes measurements by impedance: a review of bioimpedance spectroscopy (BIS) and bioimpedance analysis (BIA) methods. Med Eng Phys 2008;30 (10):1257–1269

10 Popiolek-Kalisz J, Szczygiel K. Bioelectrical impedance analysis and body composition in cardiovascular diseases. Curr Probl Cardiol 2023;48(11):101911

11 Kessler D. A novel approach using continuous monitoring of peripheral edema in heart failure patients allows recognition of acute decompensation early in the window of intervention. J Card Fail 2022;28(05):S119

12 Mabrouk S, Hersek S, Jeong HK, et al. Robust longitudinal ankle edema assessment using wearable bioimpedance spectroscopy. IEEE Trans Biomed Eng 2020;67(04):1019–1029

13 Muñoz JD, Mosquera VH, Rengifo CF. A low-cost, portable, two-dimensional bioimpedance distribution estimation system based on the AD5933 impedance converter. HardwareX 2022;11: e00274

14 Mabrouk S, Whittingslow D, Inan OT. Robust method for mid-activity tracking and evaluation of ankle health post-injury. IEEE Trans Biomed Eng 2021;68(04):1341–1350

15 Alvarez-Perez MG, Garcia-Murillo MA, Cervantes-Sánchez JJ. Robot-assisted ankle rehabilitation: a review. Disabil Rehabil Assist Technol 2020;15(04):394–408

16 Edwick DO, Hince DA, Rawlins JM, Wood FM, Edgar DW. Bioimpedance spectroscopy is a valid and reliable measure of edema following hand burn injury (part 1—method validation). J Burn Care Res 2020;41(04):780–787

17 Berkebile JA, Mabrouk SA, Ganti VG, Srivatsa AV, Sanchez-Perez JA, Inan OT. Towards estimation of tidal volume and respiratory timings via wearable-patch-based impedance pneumography in ambulatory settings. IEEE Trans Biomed Eng 2022;69(06): 1909–1919

18 Scagliusi SF, Giménez L, Pérez P, et al. Bioimpedance spectroscopy-based edema supervision wearable system for non-invasive monitoring of heart failure. IEEE Trans Instrum Meas 2023; 69:1–8

19 Ben Atitallah B, Kallel AY, Bouchaala D, Derbel N, Kanoun O. Comparative study of measurement methods for embedded bioimpedance spectroscopy systems. Sensors (Basel) 2022;22(15): 5801

20 Kassanos P, Seichepine F, Yang GZ. A comparison of front-end amplifiers for tetrapolar bioimpedance measurements. IEEE Trans Instrum Meas 2020;70:1–14

 

21 Manci E, Gümüş H, Kayatekin BM. Validity and reliability of the wearable bioelectrical impedance measuring device. Sporve Performans Araştırmaları Dergisi 2019;10(01):44–55
22 Mark T. Medical electrical equipment part 1: general requirements for basic safety and essential performance. 2014
23 Ghita M, Birs IR, Copot D, et al. Bioelectrical impedance analysis of thermal-induced cutaneous nociception. Biomed Signal Process Control 2023;83:104678
24 Ducharme JB, Hall H, Fennel ZJ, et al. Worth the wait? Time course of supine shifts in body water compartments on variables of bioelectrical impedance analysis. J Electr Bioimpedance 2023;13(01):96–105
25 Antle DM, Cormier L, Findlay M, Miller LL, Côté JN. Lower limb blood flow and mean arterial pressure during standing and seated work: Implications for workplace posture recommendations. Prev Med Rep 2018;10:117–122