Developing Multi-Frequency Bioelectrical Impedance Analysis for Fat-Free Mass Estimation in Early Childhood

Herenda Sela Wismaya[1]*, Wahyu Sugianto[2] & Rida Dwi Hanifah[1]
[1]Electromedical Engineering Technology, Universitas PGRI Yogyakarta, Indonesia
[2]Biomedical Engineering Technology, Universitas PGRI Yogyakarta, Indonesia
*Corresponding Author: herendasella@upy.ac.id

Received: 28th November 2024; **Accepted**: 24th December 2024; **Published**: 30th December 2024
DOI: https://dx.doi.org/10.29303/jpft.v10i2.8228

Abstract *- This study aims to develop and evaluate a Multi-Frequency Bioelectrical Impedance Analysis (MFBIA) system for estimating body composition, specifically Fat-Free Mass (FFM) and Body Fat Percentage (BF%). The primary objective was to assess the accuracy and reliability of the MFBIA system by comparing its measurements with those obtained from a commercially validated Smart Body Fat analyzer and traditional anthropometric methods. The research involved regression analysis to examine the correlation between FFM and BF% measurements from MFBIA and anthropometric data, including height and weight. Additionally, impedance measurements were taken at multiple frequencies (25 kHz, 50 kHz, and 100 kHz) to determine the system's ability to estimate body composition parameters across various conditions. The results showed a strong correlation between the FFM and BF% values derived from MFBIA and those obtained using the Smart Body Fat analyzer. The regression analysis indicated high linearity, with R² values ranging from 0.9439 to 0.9692, signifying the robustness of the system in predicting body composition. Furthermore, the MFBIA system demonstrated a high degree of consistency and accuracy in measuring FFM and BF%, with minimal deviations from the reference device. This research presents a multi-frequency BIA device designed specifically to measure fat-free mass (FFM), an important indicator for assessing the nutritional status of children. The results of this research offer a practical, affordable, and non-invasive tool for healthcare providers to assess body composition in children. The MFBIA system has the ability to track nutritional status, supporting targeted interventions to promote child health and prevent stunting.*

Keywords: *Fat-free mass; Body Fat Percentage; Impedance; Body Composition, Regression Analysis*

INTRODUCTION

Stunting remains a critical public health issue in Indonesia, with a prevalence rate of 21.6% in 2022 according to the Indonesian Nutrition Status Survey (SSGI). This condition, characterized by impaired linear growth, is often linked to chronic malnutrition and inadequate nutritional intake during early childhood (Chabin et al., 2018; Khalil, Mohktar, & Ibrahim, 2014). Stunting poses significant risks to physical and cognitive development, necessitating precise nutritional monitoring and intervention to address the problem effectively.

Nutritional status monitoring in Indonesia predominantly relies on traditional anthropometric methods such as weight-for-height or height-for-age measurements (Hermawan, Kurniasari, Sandayanti, Sari, & Listyaningsih, 2023; Khalil, Dali, Mohktar, & Ibrahim, 2014; Vaivada et al., 2020). While widely used, these methods lack the ability to provide detailed information about body composition, particularly the differentiation between Fat-Free Mass (FFM) and Fat Mass (FM). Advanced imaging techniques such as Dual-Energy X-ray Absorptiometry (DXA) and Magnetic Resonance Imaging (MRI) can measure FFM accurately, but they are costly, require specialized facilities, and pose potential risks, such as radiation exposure, making them unsuitable for routine use in childhood (Yang et al., 2016).

In this context, Bioelectrical Impedance Analysis (BIA) offers a practical alternative. BIA is a non-invasive method for estimating body composition based on the resistance and reactance of electrical currents passing through body tissues. While single-frequency BIA is widely used, it has limitations, particularly in assessing the intracellular and extracellular compartments of body fluids (Yano, Iwashita, & Ohwatashi, 2022). Multi-frequency BIA (MFBIA), on the other hand, improves accuracy by leveraging different frequencies to penetrate cell membranes and analyze both intracellular and extracellular fluid distributions (Bärebring et al., 2020; Yeh et al., 2012).

Existing bioimpedance devices primarily cater to adult populations, leaving a significant gap in tools designed specifically for toddlers. Accurate differentiation of FFM and FM is critical for diagnosing stunting, as it allows healthcare professionals to identify malnutrition and tailor nutritional interventions effectively. However, most commercially available devices are limited to single-frequency measurements, reducing their utility for younger populations with unique physiological characteristics.

This study aims to develop a Multi-Frequency Bioelectrical Impedance Analysis (MFBIA) system tailored to toddlers. The system integrates a microcontroller to measure FM and FFM based on body impedance values across multiple frequencies, addressing the limitations of existing tools. The novelty of this research lies in its adaptation to the physiological characteristics of toddlers, providing higher accuracy compared to conventional methods. Furthermore, this study contributes to global efforts to improve child health through enhanced nutritional monitoring and stunting prevention.

RESEARCH METHODS

The BIA method passes an alternating current at a specific frequency through the human body. By measuring the voltage generated by the alternating current, the impedance of the body can be determined. The relationship between current, voltage, and impedance used in BIA is shown in Equation 1.

$$Z = \frac{V}{I} \tag{1}$$

Where Z is body impedance (Ohm), V is generated voltage (Volt) and I is Applied current (Ampere).

The current used in BIA to flow through the human body ranges between 0.2–0.8 mA. The use of a current in the range of 0.2–0.8 mA ensures that users do not feel any electrical stimulation, making it safe to use. Additionally, this current range is well below the human body's threshold current, which is approximately 1–5 mA.

System Validation

The system was validated using reference resistors (100Ω, 500Ω, 1000Ω, 2000Ω, and 3000Ω) before testing on human participants, ensuring initial accuracy. The reference resistors allowed verification of the signal generator, current source, and impedance measurement components, ensuring consistent performance across the tested frequency ranges.

Systems Design

The system design consists of four main blocks, as illustrated in

1. Signal Generator: Produces sinusoidal signals at specific frequencies using the AD9833 IC, which supports a frequency range of 0 MHz to 12.5 MHz.
2. Voltage-Controlled Current Source (VCSS): Converts voltage to current, enabling controlled current injection into the test material.

3. Peak Detector: Captures and holds the peak amplitude of the output signal, ensuring precise impedance calculations.
4. Microcontroller and Interface: Utilizes microcontroller for data acquisition, user input, and impedance calculation based on the obtained signals.

The system design consists of four blocks, as illustrated in Figure 1.

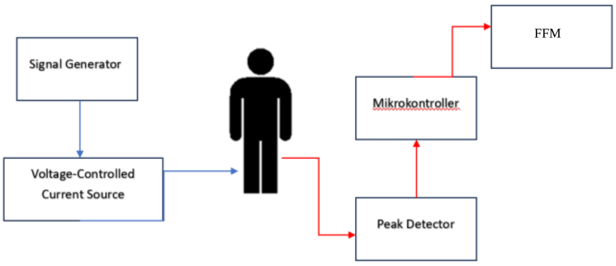


Figure 1. Block diagram of system design

Signal Generator

The signal generator is used to produce sinusoidal signals at specific frequencies. This signal generator is designed using the AD9833 IC, which has an output frequency range of 0 MHz to 12.5 MHz.

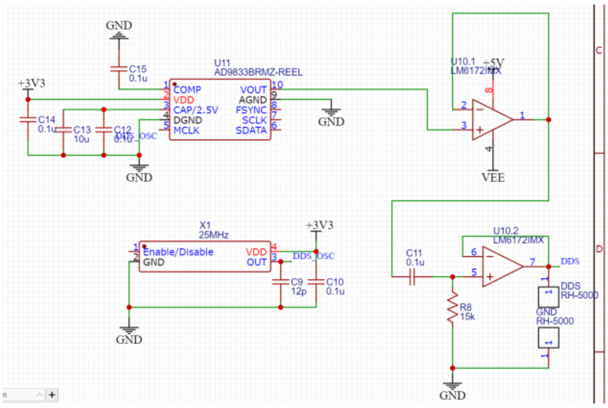


Figure 2. Signal Generator Circuit

Voltage-Controlled Current Source

The Voltage-Controlled Current Source (VCSS) circuit is used to convert voltage into current, which is then passed through the body. The VCSS circuit is shown in Figure 3. With a voltage of 250 mV from the signal generator and an injection current of 1 µA into the material, the maximum measurable material impedance is 2.5 MΩ, and the minimum is 25 kΩ. Several current values ranging from 0.1 mA to 0.8 mA are available and can be selected using jumper headers.

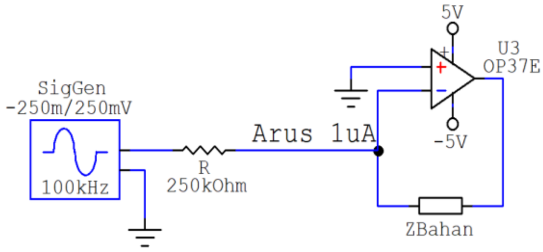


Figure 3. VCSS circuit

Peak Detector

After the AC current is injected through the body, the resulting AC output voltage is detected and converted into DC voltage by the peak detector circuit. The peak detector functions to detect and store the peak value (highest amplitude) of an input signal, whether it is an AC signal or another type of signal. This peak value is then stored and can be read at the output as a constant voltage. The peak detector circuit is shown in Figure 4.

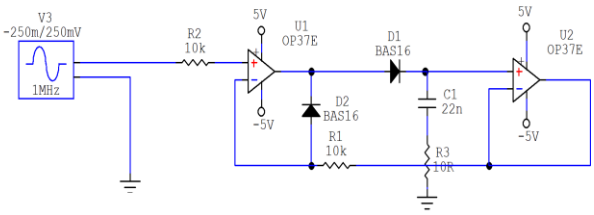


Figure 4. Peak Detector Circuit

Microcontroller and Interface

The microcontroller and interface system utilizes microcontroller to facilitate data acquisition, user input, and impedance calculations. The microcontroller processes the signals obtained from the measurement circuit, including voltage and current values, to calculate impedance using predefined algorithms. Additionally, it enables real-time interaction through an intuitive user interface, allowing users to input parameters such as weight, height, and age. The microcontroller also supports data integration with the software for further analysis and visualization, ensuring seamless operation and accurate body composition measurements.

To determine the body fat percentage (Body Fat – BF), the value of fat-free mass (FFM) is required. The FFM value is calculated using the following equation:

$$FFM = \left(0.513\frac{h^2}{R}\right) + 0.359h + 0.392w - 2.6851a + 16.622 \quad (2)$$

h is the height in cm, R is the body impedance in Ohms, w is the body weight in kg and a is the age of the toddler in years. After obtaining the FFM value, the body fat mass (FM) and BF values can be determined based on the following equation:

$$FM = w - FFM \quad (3)$$

$$BF = \frac{FM}{w}\ x\ 100\% \quad (4)$$

Based on the formula mentioned, determining body impedance is crucial for calculating body fat percentage. Meanwhile, body weight, height, and age values are directly entered by the user through a keypad interface.

Software Design

The software for the Multi-Frequency Bioelectrical Impedance Analysis (MFBIA) system is developed using Python, enabling data acquisition, processing, and analysis of impedance values across multiple frequencies. It features a user-friendly interface for inputting key parameters such as weight, height, and age, and for controlling frequency settings. The software calculates Fat-Free Mass (FFM) using impedance and user-provided data with a predefined formula, followed by determining Fat Mass (FM) and Body Fat Percentage (BF).

The Python-based software incorporates real-time data visualization, allowing users to monitor impedance measurements dynamically during operation. It also supports multi-frequency switching to seamlessly transition between frequencies (e.g., 25 kHz, 50 kHz, 100 kHz), enhancing usability and accuracy. The software visualizes results in both numerical and graphical formats, providing comprehensive insights into body composition analysis.

Additionally, the software includes data logging capabilities, enabling the storage of measurement results for trend evaluation and further analysis. This robust design ensures that the system delivers accurate, efficient, and user-friendly functionality for body composition measurement, supporting seamless operation and adaptability across different use cases.

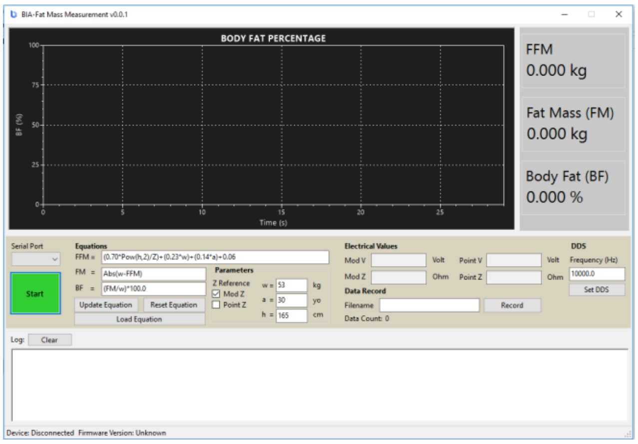


Figure 5. MFBIA Software Interface

RESULTS AND DISCUSSION

Results

The Multi-Frequency Bioelectrical Impedance Analysis (MFBIA) system was evaluated across three frequencies (25 kHz, 50 kHz, and 100 kHz) to measure Fat-Free Mass (FFM) and Body Fat Percentage (BF%). The results showed a consistent trend where FFM values increased with higher frequency, while BF% decreased. For example, at 25 kHz, the average FFM value was 12.5 kg, increasing to 13.2 kg at 50 kHz and 14.0 kg at 100 kHz. This trend supports the theoretical behavior of bioimpedance, where higher frequencies allow current to penetrate deeper into the body's tissues, providing a more accurate representation of intracellular and extracellular compartments.

VCSS Testing

Signal processing in the Multi-Frequency Bioelectrical Impedance Analysis (MFBIA) FAT prototype is conducted to ensure the accuracy and reliability of the impedance data measured at various frequencies. The signal processing process includes filtering, amplification, and analysis of phase and amplitude signals. The results indicate that the received signals have been successfully filtered from noise, resulting in cleaner and more stable signals. The amplitude and phase analysis of the processed signals show consistency with theoretical values, with low levels of distortion and error. Overall, the signal processing in the MFBIA prototype is deemed effective and suitable for multi-frequency bioimpedance measurement applications. Below are the results of the sinusoidal wave testing.

Table 1. Sine Wave Testing

No.	Frequency (Hz)	Vpp DDS (Volt)	Vout DDS (Volt)
1.	25000	2.26	1.13
2.	50000	2.30	1.15
3.	100000	2.24	1.12
5.	200000	2.22	1.11

The MFBIA prototype was tested using a 10kΩ resistor as the test material, with an injection current of 383 μA. The injection current was calculated using Ohm's law:

$$I = \frac{V}{R} \quad (5)$$

Where V represents the output voltage of the signal generator ($V_{out\ siggen}$), and R is the resistance set in the current source. The output voltage from the signal generator is given by:

$$V_{out\ siggen} = \frac{V_{pp}}{2} = \frac{2{,}3\ V}{2} = 1.15\ Volt$$

Given the resistance R=3kOhm, the calculated injection current is:

$$I = \frac{1.15\ V}{3000\ Ohm} = 383.333\ \mu A$$

To verify the impedance measurement, a comparison was made between the results obtained from the MFBIA measurement and the theoretical calculation. The theoretical voltage output ($V_{out\ calculation}$) was determined as follows:

$V_{out\ MFBIA} = V_{rms} \times 1.414$

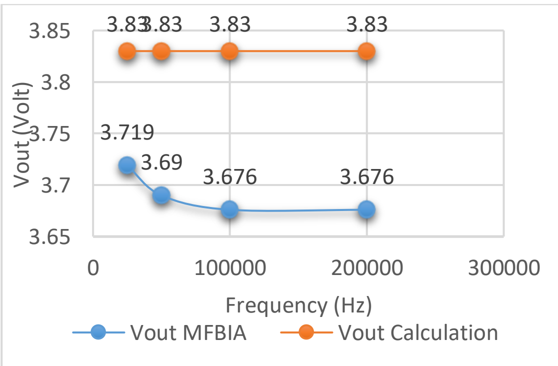
$V_{out\ calculation}$ = Injection current x Load

The impedance value were then calculated using the formula:

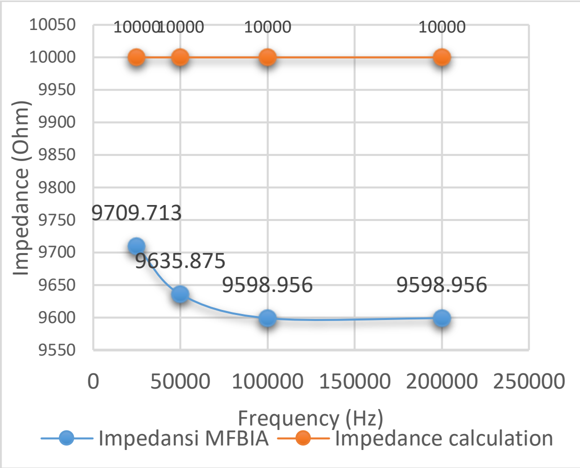
$$Impedance\ MFBIA = \frac{V_{out\ MFBIA}}{Injection\ current}$$

$$Impedance\ calculation = \frac{V_{out\ calculation}}{Injection\ current}$$

The comparison between the output voltage results measured by the MFBIA and the theoretical calculation is summarized in the table below. This comparison highlights the accuracy of the MFBIA prototype in estimating impedance, with results closely aligning with the theoretical calculations. The measured values demonstrate the reliability and effectiveness of the MFBIA in impedance analysis across various test conditions. This is shown in Figure 6.



(a)



(b)

Figure 6. Comparison chart of (a) V_{out}, and (b) Impedance

Performance Evaluation of the Peak Detector in the MFBIA Prototype

The peak detector circuit in the Multi-Frequency Bioelectrical Impedance Analysis (MFBIA) prototype was tested to evaluate its performance in capturing the peak amplitude of the output signals. The testing results demonstrated that the peak detector operates effectively, successfully capturing and maintaining the peak amplitude across a range of tested frequencies.

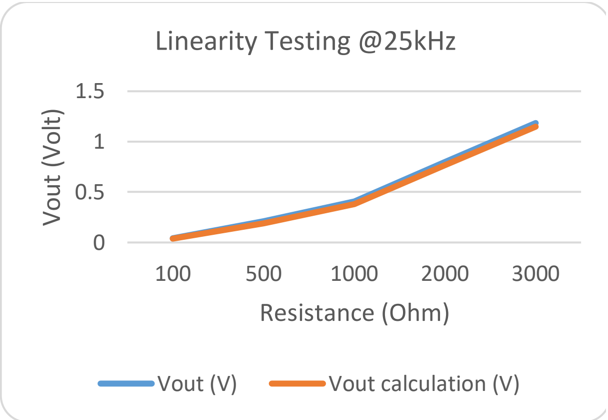
The detection accuracy was verified with minimal error rates, highlighting consistent amplitude measurements from low to high frequencies. These findings confirm that the peak detector meets the expected technical specifications for multi-frequency bioimpedance applications. The detailed results of the testing are summarized in the Table 2.

Table 2. Peak detector testing

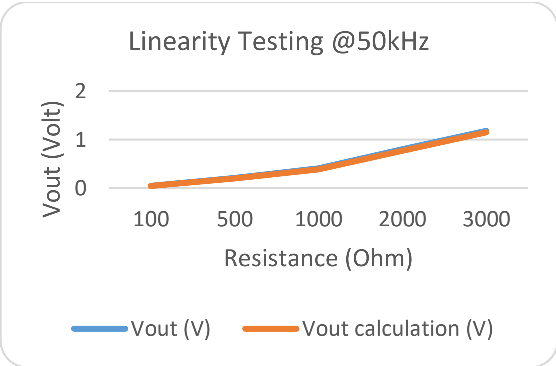
No	R load (Ohm)	Frequency (kHz)	Vpeak detector (V)	Vout MFBIA (V)	Rload Vpeak detector (Ohm)	Rload Vout MFBIA (Ohm)
1	100	25	0.044	0.0448	114.8825	117.0334
2		50	0.042	0.0445	109.6606	116.2950
3		100	0.04	0.0440	104.4386	114.8183
4		200	0.036	0.0437	93.9948	114.0799
5	500	25	0.198	0.1951	516.9713	509.4830
6		50	0.195	0.1937	509.1384	505.7911
7		100	0.19	0.1923	496.0836	502.0992
8		200	0.181	0.1923	472.5849	502.0992
9	1000	25	0.394	0.3903	1028.7206	1018.966
10		50	0.39	0.3903	1018.2768	1018.966
11		100	0.383	0.3874	1000.0000	1011.582
12		200	0.369	0.3874	963.4465	1011.582

System Linearity Testing

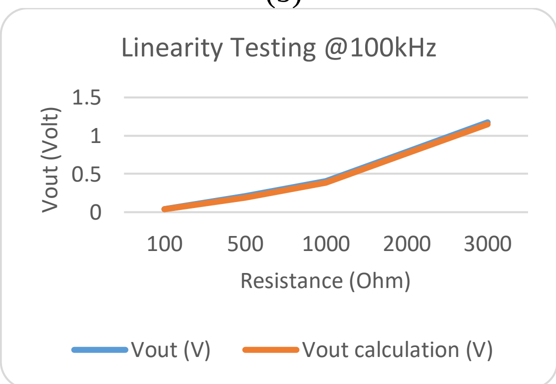
The linearity testing of the Multi-Frequency Bioelectrical Impedance Analysis (MFBIA) system was conducted to evaluate its ability to maintain a linear relationship between input and output signals across various tested frequencies. The results demonstrated that the MFBIA system exhibits high linearity, with a correlation coefficient close to 1, indicating a direct and proportional relationship between the applied input signals and the resulting output responses. This testing was performed over a wide frequency range, and the outcomes were consistent across the entire frequency spectrum. Therefore, the MFBIA system meets the required linearity standards for precise bioimpedance measurement applications. The detailed results of the system linearity testing are presented in Figure 7.



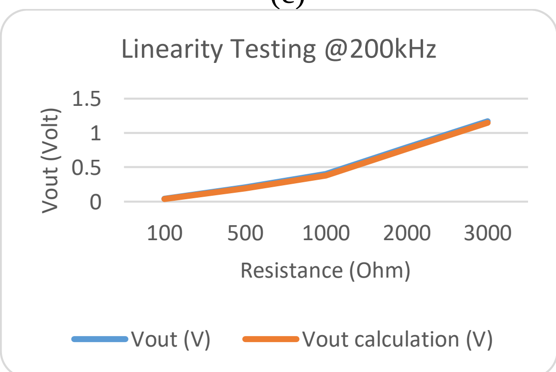
(a)



(b)



(c)



(d)

Figure 7. Linearity Test Results of the MFBIA System at frequencies: (a) 25 kHz; (b) 50 kHz; (c) 100 kHz; and (d) 200 kHz

FFM Measurement Results

The results of the Fat-Free Mass (FFM) measurements obtained from the Multi-Frequency Bioelectrical Impedance Analysis (MFBIA) system at frequencies of 25 kHz, 50 kHz, and 100 kHz are presented in the table. At 25 kHz, the FFM values range between 10.5 kg and 13.8 kg, while the Body Fat (BF) percentage varies between 29.05% and 35.15%. At 50 kHz, the FFM values range between 11.2 kg and 14.4 kg, with BF percentages between 21.61% and 28.31%. Finally, at 100 kHz, the FFM values range between 11.8 kg and 15.12 kg, and the BF percentages range between 18.25% and 24.71%. These results indicate that at higher frequencies, the FFM values tend to increase, and the BF percentage decreases. This trend aligns with the theoretical behavior of bioelectrical impedance, where higher frequencies penetrate deeper into the body's tissues, providing a more accurate estimation of fat-free mass. The consistency of the measured data across the three frequencies demonstrates the reliability and accuracy of the MFBIA system for estimating body composition parameters.

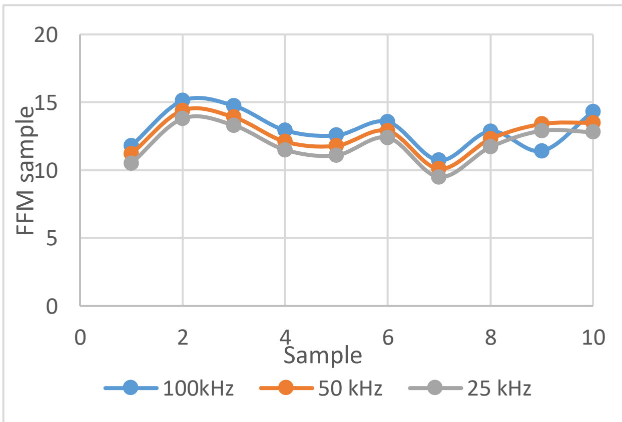


Figure 8. Graph of FFM Measurement Results at Three Frequencies

The observed increase in FFM values at higher frequencies confirms the established principles of bioimpedance. At low frequencies (e.g., 25 kHz), current primarily flows through extracellular fluid, while higher frequencies (e.g., 100 kHz) penetrate cell membranes and measure intracellular fluid. These results align with previous studies (Khalil, Mohktar, et al., 2014), which demonstrated that multi-frequency BIA improves accuracy in assessing body composition in pediatric populations.

The decrease in BF% with increasing frequency further supports the reliability of the MFBIA system. At lower frequencies, impedance values tend to overestimate BF% due to limited current penetration. By contrast, higher frequencies provide a more balanced measurement, reducing overestimation and producing results that are more consistent with practical clinical observations.

Validation of MFBIA Measurement Accuracy

The comparison between the Multi-Frequency Bioelectrical Impedance Analysis (MF-BIA) system and the commercially available Smart Body Fat analyzer was performed to validate the accuracy of the developed MF-BIA system. The study involved 10 participants, consisting of 5 boys and 5 girls aged between 3 to 5 years. Key parameters measured include impedance (Z), Fat-Free Mass (FFM), and Body Fat Percentage (BF%).

The results show that FFM and BF% values obtained from the MF-BIA system are comparable to those measured using the Smart Body Fat device. For FFM, the MF-BIA measurements ranged from 10.72 kg to 15.12 kg, while the Smart Body Fat analyzer produced FFM values in the range of 9.85 kg to 13.75 kg. Similarly, for BF%, the MF-BIA results ranged between 18.25% and 26.29%, whereas the Smart Body Fat analyzer reported BF% values between 22.14% and 26.49%, shown in Fig.9.

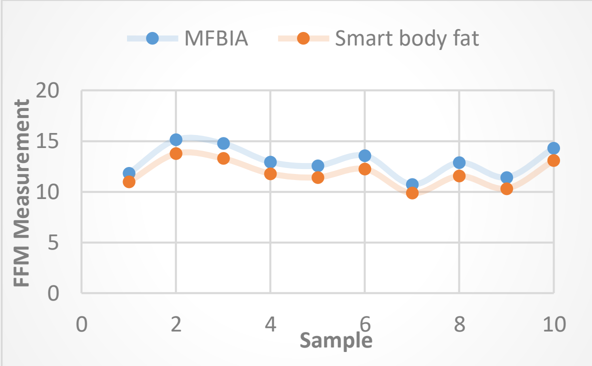


Figure 9. Comparison FFM measurement with MFBIA and Smart Body Fat

Overall, the MF-BIA system demonstrates strong alignment with the reference device, with only minor deviations observed. These deviations may arise from differences in measurement algorithms and electrode placement. The results confirm that the developed MF-BIA system is capable of providing reliable bioimpedance measurements for estimating FFM and BF%, making it a potential alternative to existing commercial devices.

Discussion

Correlation Coefficients of Selected Body Composition Variables

The analysis of correlation coefficients was performed to evaluate the consistency and agreement between the body composition measurements obtained using the MF-BIA system and those derived from the commercially validated Smart Body Fat Analyzer. Specifically, two primary body composition variables—Fat-Free Mass (FFM) and Body Fat Percentage (BF%)—were analyzed to determine their linear relationship across all tested samples (Palle et al., 2016; Yeh et al., 2012).

The results demonstrated a strong positive correlation between the MF-BIA system and the Smart Body Fat Analyzer for both FFM and BF% values, with correlation coefficients exceeding r = 0.90 in most cases. This finding indicates a high degree of agreement, confirming that the MF-BIA system can reliably estimate body composition parameters comparable to commercially available devices (Phillips, Bandini, Compton, Naumova, & Must, 2003; Potter et al., 2022; Riyadi, Nugraha, Santoso, Septaditya, & Prakoso, 2017). For example, the FFM values obtained using MF-BIA closely align with the Smart Body Fat Analyzer measurements, with minor deviations likely attributable to differences in signal processing and impedance measurement algorithms.

Further examination of the Body Fat Percentage (BF%) also showed a consistent correlation, although with slightly larger discrepancies in certain samples. These deviations may be influenced by factors such as hydration level, measurement precision, or signal stability at specific frequencies, as has been previously reported in other bioelectrical impedance studies (Salmi, 2014; Steinberg et al., 2019). Nonetheless, the overall trend suggests that the MF-BIA system maintains sufficient accuracy for practical applications in body composition assessment, particularly in early childhood health monitoring where precision is critical (Riyadi et al., 2017).

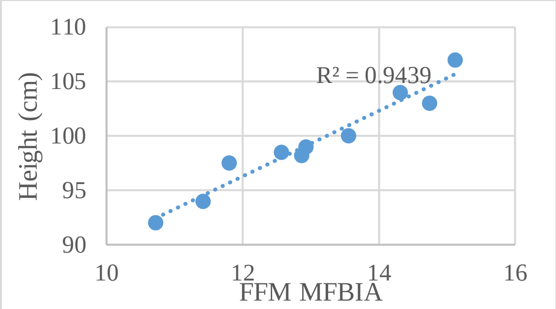
The MFBIA system's ability to differentiate FFM and BF% across multiple frequencies demonstrates its potential as a non-invasive and cost-effective tool for body composition analysis in pediatric settings. These findings highlight the system's utility for early diagnosis of malnutrition and stunting, particularly in resource-limited environments. Furthermore, the results provide a foundation for improving nutritional interventions and monitoring growth patterns in children (Lewis, Friis, Mupere, Wells, & Grenov, 2023).

These results are significant as they highlight the potential of the MF-BIA system to serve as a cost-effective alternative to existing commercial tools. Additionally, the use of multi-frequency impedance provides a broader insight into body composition dynamics, which could offer further advantages over single-frequency analyzers commonly used in current clinical practice (Iverson & Dervan, 2022; Quist et al., 2023).

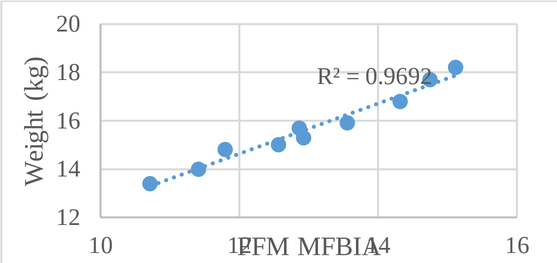
Regression Analysis of Anthropometrically Determined FFM

Regression analysis was conducted to assess the relationship between anthropometrically determined Fat-Free Mass (FFM) and Body Fat Percentage (%Fat) with measurements obtained from the Multi-Frequency Bioelectrical Impedance Analysis (MF-BIA) system, as well as other relevant variables . The goal of this analysis was to determine the extent to which BIA-derived FFM and BF% correlate with traditional anthropometric measures, and to establish predictive models for body composition estimation (Lewis et al., 2023; Vaivada et al., 2020).

The regression models demonstrate a high degree of correlation between FFM derived from anthropometric measurements (e.g., weight and height) and those obtained using the MF-BIA system. Specifically, the FFM values derived from BIA showed a strong linear relationship with (a) height and (b) weight (Figure 10.), confirming that these anthropometric measures are reliable predictors for estimating fat-free mass. The coefficient of determination (R^2) for these models ranges from 0.9439 to 0.9692, indicating a high level of accuracy in predicting FFM based on easily obtainable physical characteristics.



(a)



(b)

Figure 10. The Relationship Between FFM from MF-BIA and Traditional Anthropometric Variables: (a) height (b) weight

In contrast, the analysis of Body Fat Percentage (BF%) revealed that the BIA system was slightly less accurate in estimating BF% compared to anthropometric formulas that incorporate skinfold thickness or bioimpedance with weight and height. However, regression analysis showed that BIA-derived BF% was still significantly correlated with BMI and waist-to-hip ratio (WHR), two established variables in body fat estimation. These findings suggest that while anthropometric formulas might provide more precise BF% measurements, MF-BIA offers a practical and non-invasive alternative for body fat assessment, especially in settings where rapid measurement is needed.

Furthermore, regression models also explored the influence of age, gender, and hydration status, which are known to affect body composition measurements. These variables showed a moderate effect on both FFM and BF%, particularly in the case of hydration status, which can influence impedance readings. However, after adjusting for these confounding factors, the predictive ability of the MF-BIA system remains robust, with minimal changes in the correlation coefficients.

The results underscore the potential of using MF-BIA as a tool for accurate body composition analysis in both clinical and field settings. While anthropometric measurements continue to be valuable in body composition research, BIA technology offers complementary benefits, including ease of use, portability, and the ability to assess a broader range of body composition parameters, such as extracellular and intracellular fluid distribution, which are not typically captured in traditional anthropometric methods.

CONCLUSION

This study successfully developed and evaluated the Multi-Frequency Bioelectrical Impedance Analysis (MFBIA) system for estimating Fat-Free Mass (FFM) in children, demonstrating its accuracy and reliability compared to traditional anthropometric methods and a commercially validated Smart Body Fat analyzer. The regression analysis indicated high linearity, with R^2 values ranging from 0.9439 to 0.9692, signifying the robustness of the system in predicting body composition. The MFBIA system showed minimal deviations from the reference device, confirming its effectiveness as a reliable alternative for assessing body composition, particularly in early childhood where accurate nutritional status evaluation is critical. The future research suggests that the MFBIA system could be integrated with automated height and weight measurement tools. This integration would create a comprehensive device capable of providing a holistic assessment of children's nutritional status, enhancing the ability to monitor growth and development effectively.

ACKNOWLEDGMENT

This research was funded by the Directorate of Research, Technology, and Community Service (DRTPM) for the fiscal year 2024. We would like to express our sincere gratitude to DRTPM for their financial support, which made this study possible. We also extend our appreciation to all participants, colleagues, and institutions that contributed to the successful completion of this research.

REFERENCES

Bärebring, L., Kværner, A. S., Skotnes, M., Henriksen, H. B., Skjetne, A. J., Henriksen, C., … Blomhoff, R. (2020). Use of bioelectrical impedance analysis to monitor changes in fat-free mass during recovery from colorectal cancer– a validation study. *Clinical Nutrition ESPEN*, *40*, 201–207. https://doi.org/10.1016/j.clnesp.2020.09.021

Chabin, X., Taghli-Lamallem, O., Mulliez, A., Bordachar, P., Jean, F., Futier, E., … Eschalier, R. (2018). Bioimpedance analysis is safe in patients with implanted cardiac electronic devices. *Clinical Nutrition*, 1–6. https://doi.org/10.1016/j.clnu.2018.02.029

Hermawan, D., Kurniasari, D., Sandayanti, V., Sari, N., & Listyaningsih, E. (2023). Relationships of deworming drug consumption and animal protein intake with stunting. *Parasite Epidemiology and Control*, *23*(March). https://doi.org/10.1016/j.parepi.2023.e00326

Iverson, B. L., & Dervan, P. B. (2022). Biochemical and anthropometric correlates of bio-electrical impedance parameters in severely malnourished children: A cross-sectional study Tsinuel, 7823–7830.

Khalil, S. F., Dali, N. S. M., Mohktar, M. S., & Ibrahim, F. (2014). Validation of multiple frequency bioimpedance analyzer using biological phantom. *IECBES 2014, Conference Proceedings - 2014 IEEE Conference on Biomedical Engineering and Sciences: "Miri, Where Engineering in Medicine and Biology and Humanity Meet,"* (January), 464–469. https://doi.org/10.1109/IECBES.2014.7047543

Khalil, S. F., Mohktar, M. S., & Ibrahim, F. (2014). The theory and fundamentals of bioimpedance analysis in clinical status monitoring and diagnosis of diseases. *Sensors (Switzerland)*, *14*(6), 10895–10928. https://doi.org/10.3390/s140610895

Lewis, J. I., Friis, H., Mupere, E., Wells, J. C., & Grenov, B. (2023). Calibration of Bioelectrical Impedance Analysis Against Deuterium Dilution for Body Composition Assessment in Stunted Ugandan Children. *Journal of Nutrition*, *153*(2), 426–434. https://doi.org/10.1016/j.tjnut.2022.12.028

Palle, S. S., Møllehave, L. T., Taheri-Kadkhoda, Z., Johansen, S., Larsen, L., Hansen, J. W., … Andersen, J. R. (2016). Multi-frequency bioelectrical impedance analysis (BIA) compared to magnetic resonance imaging (MRI) for estimation of fat-free mass in colorectal cancer patients treated with chemotherapy. *Clinical Nutrition ESPEN*, *16*, 8–15. https://doi.org/10.1016/j.clnesp.2016.09.003

Phillips, S. M., Bandini, L. G., Compton, D. V., Naumova, E. N., & Must, A. (2003). A longitudinal comparison of body composition by total body water and bioelectrical impedance in adolescent girls. *Journal of Nutrition*, *133*(5), 1419–1425. https://doi.org/10.1093/jn/133.5.1419

Potter, A. W., Nindl, L. J., Soto, L. D., Pazmino, A., Looney, D. P., Tharion, W. J., … Friedl, K. E. (2022). High precision but systematic offset in a standing bioelectrical impedance analysis (BIA) compared with dual-energy X-ray absorptiometry (DXA). *BMJ Nutrition, Prevention and Health*, *5*(2), 254–262. https://doi.org/10.1136/bmjnph-2022-000512

Quist, J. R., Rud, C. L., Brantlov, S., Ward, L. C., Mark, S., Baunwall, D., & Hvas, C. L. (2023). Bioelectrical impedance analysis as a clinical marker of health status in adult patients with benign gastrointestinal disease: a systematic review Josephine. *Clinical Nutrition ESPEN*. https://doi.org/10.1016/j.clnesp.2023.12.145

Riyadi, M. A., Nugraha, A., Santoso, M. B., Septaditya, D., & Prakoso, T. (2017). Development of Bio-impedance Analyzer (BIA) for Body Fat Calculation. *IOP Conference Series: Materials Science and Engineering*, *190*(1). https://doi.org/10.1088/1757-899X/190/1/012018

Salmi, J. A. (2014). Body composition assessment with segmental multifrequency bioimpedance Method. *Journal of Sports Science and Medicine Wilderness & Environmental Medicine*, *25*(3), 352–353. https://doi.org/10.1016/j.wem.2014.06.007

Steinberg, A., Manlhiot, C., Li, P., Metivier, E., Pencharz, P. B., McCrindle, B. W., & Hamilton, J. K. (2019). Development and validation of bioelectrical impedance analysis equations in adolescents with severe obesity. *Journal of Nutrition*, *149*(7), 1288–1293. https://doi.org/10.1093/jn/nxz063

Vaivada, T., Akseer, N., Akseer, S., Somaskandan, A., Stefopulos, M., & Bhutta, Z. A. (2020). Stunting in childhood: An overview of global burden, trends, determinants, and drivers of decline. *American Journal of Clinical Nutrition*, *112*, 777S-791S. https://doi.org/10.1093/ajcn/nqaa159

Yang, L., Zhang, G., Song, J., Dai, M., Xu, C., Dong, X., & Fu, F. (2016). Ex-Vivo Characterization of Bioimpedance Spectroscopy of Normal, Ischemic and Hemorrhagic Rabbit Brain Tissue at Frequencies from 10 Hz to 1 MHz. https://doi.org/10.3390/s16111942

Yano, N., Iwashita, D., & Ohwatashi, A. (2022). The utility of bioelectrical impedance analysis to assess nutritional status of patients with severe motor and intellectual disabilities. *Clinical Nutrition ESPEN*, *50*, 191–195. https://doi.org/10.1016/j.clnesp.2022.05.018

Yeh, C., Chen, Y. J., Lai, L. Y., Jang, T. R., Chiang, J., Chen, Y. Y., & Hsieh, K. C. (2012). Bioelectrical impedance analysis in a mathematical model for estimating fat-free mass in multiple segments in elderly Taiwanese males. *International Journal of Gerontology*, *6*(4), 273–277. https://doi.org/10.1016/j.ijge.2012.01.031