Calf Bioimpedance Analysis: A Novel Approach for Evaluating Hydration Status in Pediatric Dialysis Patients Under High Dialysate Sodium

Mohammad Firouzmand,[1]* Shahrokh Noori,[1] Vahid Reza Nafisi,[1] Nakysa Hooman[2]

Original Paper

[1]Department of Biomedical Engineering, Iranian Research Organization for Science & Technology (IROST) Tehran, Iran
[2]Professor of Pediatric Nephrology, Ali –Asghar Clinical Research Development Center, Department of Pediatrics, School of Medicine, Iran University of Medical Sciences, Tehran, Iran

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Introduction. Assessment of hydration status in pediatric hemodialysis is complicated by dynamic fluid shifts and sodium variability. Conventional methods such as clinical evaluation and whole-body bioimpedance analysis (BIA) lack precision for individual-level monitoring. This study introduces a calf impedance ratio (ΔZ_{15kh} / ΔZ_{150kh}) to classify fluid responses and evaluate the impact of high dialysate sodium (143 mEq/L) on fluid dynamics and blood pressure.

Methods. A cross-sectional study was conducted involving 14 children aged 5–12 years undergoing maintenance hemodialysis. Impedance was measured pre- and post-dialysis at two frequencies using a custom-built device. The raw impedance changes were analyzed without conversion to fluid volumes, allowing for classification into three physiological response groups based on the impedance ratio.

Results. Three distinct physiological profiles emerged. Group 1 ($\frac{\Delta Z_{15kh}}{\Delta Z_{150kh}} > 1$) showed effective extracellular fluid removal with stable hemodynamics. Group 2 (ratio between 0 and 1) reflected minimal Extracellular Water (ECW) ECW changes, potentially due to sodium-driven redistribution, with additional influence from sodium-enhanced tissue conductivity. Group 3 ($\Delta Z_{15kh} < 0$) exhibited paradoxical impedance decreases despite fluid removal, along with sodium increase and blood pressure elevation. ΔZ_{15kh} positively correlated with ΔBP-sys ($r = 0.650$, $P = .012$).

Conclusion. The impedance ratio ($\frac{\Delta Z_{15kh}}{\Delta Z_{150kh}}$) provides a sensitive index for classifying fluid responses and identifying sodium-related effects in pediatric hemodialysis. It may support individualized dialysis prescriptions by guiding adjustments in ultrafiltration and dialysate sodium to improve hemodynamic stability and fluid balance.

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INTRODUCTION

Effective fluid management is essential for optimizing outcomes in hemodialysis (HD), particularly in pediatric patients, where physiological variability and treatment responses differ markedly from adults. Achieving the appropriate fluid balance requires accurate adjustment of ultrafiltration (UF) and dialysate sodium concentration to ensure sufficient fluid removal while minimizing hemodynamic instability, including intradialytic hypotension (IDH).[1] Current strategies for fluid management rely on the clinical estimation of dry weight (DW)—defined as the lowest weight that a patient can tolerate without signs of fluid overload or hypotension—primarily assessed through changes in body weight and blood pressure.[2,3] However, clinical assessments alone often fail to detect subclinical fluid overloads below 2–3 liters and are subject to confounding factors such as changes in body composition, delayed vascular refilling from interstitial compartments, and antihypertensive medication use.[4] Consequently, patients may complete HD sessions in a state of euvolemia, dehydration, or persistent overhydration.

Bioimpedance analysis (BIA) is a non-invasive, affordable technique for evaluating body composition and hydration status,[5-7] making it suitable for both clinical and home-based purposes.[8] However, recent studies indicate that traditional BIA methods often detect fluid changes only at the group level and lack the resolution (< 500 mL) needed for accurate assessment at the individual level.[9-10] Moreover, individual BIA estimates may have errors exceeding two liters at the beginning and approximately one liter by the end of dialysis.[11,12] These limitations underscore the importance of identifying factors that influence measurement accuracy—particularly sodium fluctuations—since discrepancies between serum and dialysate sodium concentrations can alter tissue conductivity and distort impedance-based estimations.

Intradialytic hypotension (IDH) is a common complication in HD caused by rapid fluid shifts or excessive UF, leading to an abrupt drop in blood pressure. One approach to mitigating IDH is to increase the sodium concentration in the dialysate, promoting osmotic water movement from the interstitial to the intravascular compartment. However, excessive dialysate sodium may raise serum sodium, stimulate thirst, and result in greater interdialytic fluid gain. Therefore, precise tracking of both body water and sodium dynamics is critical to guide individualized fluid prescriptions.[13]

Various overhydration indices derived from BIA have been proposed to assess fluid status in dialysis patients. Among these, the extracellular water to total body water ratio (ECW/TBW) is commonly used, with a typical threshold of > 0.40 indicating volume overload—compared to ~0.38 in healthy individuals. However, this ratio can be influenced by factors unrelated to hydration, such as alterations in sodium concentration, muscle wasting, or shifts in body composition.[14] Another commonly used marker is the overhydration to extracellular water ratio (OH/ECW), which quantifies excess fluid relative to the ECW compartment. This index has shown predictive value for adverse outcomes, including mortality and cardiovascular events. Yet, its accuracy may decline in pediatric patients or individuals with abnormal fluid distribution.[15,16] Bioimpedance vector analysis (BIVA) and phase angle (PA)—derived from the phase shift between voltage and current—have also been applied to assess hydration status `and cellular membrane integrity. While lower PA values are associated with inflammation and higher mortality, these measurements are highly sensitive to electrode placement, body geometry, and population-specific calibration models, limiting their applicability for dynamic monitoring during dialysis.[16]

Collectively, although these indices have demonstrated associations with clinical outcomes, their performance is often limited by interindividual variability, low temporal resolution, and susceptibility to errors introduced by changes in sodium levels and tissue conductivity. As such, they may not be suitable for guiding intradialytic fluid management in pediatric populations.

Novel Approaches

In a study by Zhu *et al.*, a novel overhydration index was proposed using the ratio of resistance at low and high frequencies (R_0 / R_∞). This ratio demonstrated a stronger correlation with actual fluid status compared to the traditional ECW/TBW index, suggesting that frequency-based impedance metrics may offer a more accurate assessment of volume overload in dialysis patients.[14,15,17]

Building upon this concept, the present study utilized segmental bioimpedance measurements at the lower leg (calf)—a region with a relatively uniform cylindrical geometry—to minimize geometric variability and enhance measurement precision.[18] Rather than relying on absolute ECW and TBW estimations, we focused on raw impedance changes at two distinct frequencies: ΔZ_{15kh} (reflecting extracellular water changes) and ΔZ_{150kh} (reflecting total body water changes). This dual-frequency approach was applied to assess fluid shifts prior and following dialysis, eliminating the confounding effects of volume estimation algorithms.

MATERIALS AND METHODS

Study Design and Participants

This cross-sectional study enrolled 14 pediatric patients (8 females, 6 males) aged 5 to 12 years undergoing maintenance hemodialysis at Ali Asghar Hospital in Tehran. All participants received thrice-weekly HD sessions, and their treatment regimens were managed under standard clinical protocols.

To explore the role of sodium in modulating tissue conductivity and fluid dynamics, a dialysate with high sodium concentration (143 mEq/L) was used to help prevent intradialytic hypotension (IDH). Pre- and post-dialysis serum sodium levels were measured to evaluate their influence on impedance profiles, allowing us to investigate the interaction between sodium shifts, blood pressure variations, and segmental impedance responses during dialysis.

Ultrafiltration (UF) volumes were determined by clinical assessment of interdialytic weight gain and were administered at constant rates. The sodium concentration in the dialysate was fixed at 143 mmol/L across all sessions. Blood pressure, body weight, and serum sodium levels were recorded before and after each dialysis session. Dialysis duration ranged between 2 to 4 hours, based on individual clinical needs.

Ethical Approval

Ethical approval for this study was granted by the Ethics Committee of Iran University of Medical Sciences (IR.IUMS.REC.1402.937). Informed written consent was obtained from the parents or legal guardians of all participants. Patient anonymity and confidentiality were strictly maintained throughout the study in accordance with the Declaration of Helsinki.

Bioimpedance Device and Measurement Protocol

To minimize the impact of body morphology on impedance measurements, assessments were conducted on the leg, which has a more cylindrical shape compared to all body measurement. Previous research has shown that the calf of the leg can serve as a reliable indicator of an individual's hydration status.[19-20]

Measurements were conducted using a custom-built device (MAH12 Analyzer), developed and validated by the Department of Medical Engineering, Iranian Research Organization for Science & Technology (IROST). The analyzer operates at frequencies ranging from 5 kHz to 250 kHz, using a constant current of 800 µA to measure resistance, reactance, and phase angle (Figure 1).

In this study, impedance measurements were taken at two frequencies: 15 kHz and 150 kHz, between the sole of the foot and below the knee. Impedance at 15 kHz was considered an indicator

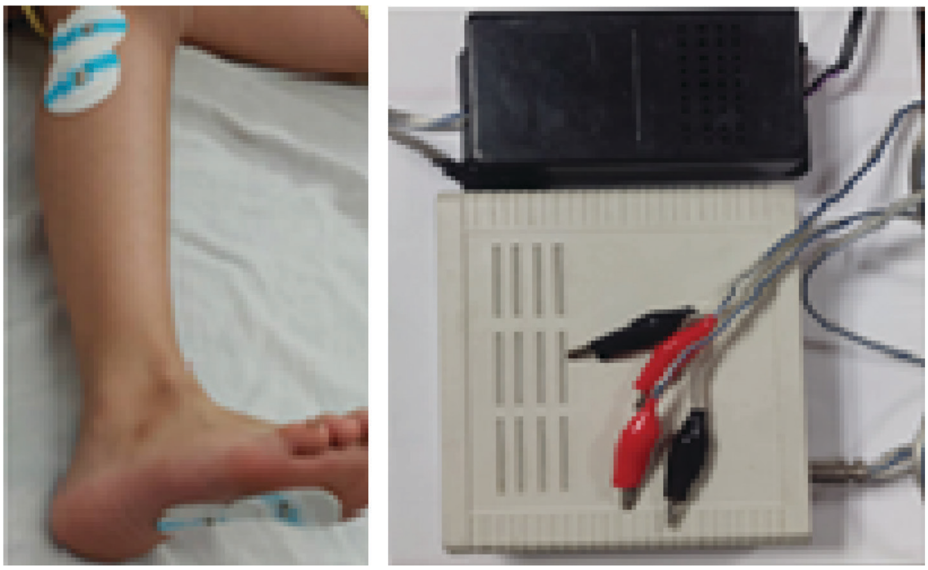

Figure 1. Bioimpedance setup and measurement

of extracellular water (ECW), while impedance at 150 kHz was considered an indicator of total body water (TBW). Ag/AgCl electrodes were used for electrode connections, and to ensure accuracy, measurements were taken five times at both the beginning and end of hemodialysis. Due to the inaccuracy of prediction algorithms for converting impedance to body water at the individual level, all analyses were conducted based on the raw impedance data changes (ΔZ_{15kh} and ΔZ_{150kh}).[11]

Statistical Analysis

Data analysis was performed using Python (version 3.9) with relevant scientific libraries (pandas, scipy, statsmodels). Variables such as changes in serum sodium (ΔNa), systolic blood pressure (ΔBP-sys), and diastolic blood pressure (ΔBP-dia) were compared across three patient groups stratified by the impedance ratio (ΔZ_{15kh} / ΔZ_{150kh}), which indicates relative shifts in ECW and TBW.

Normality was assessed using the Shapiro–Wilk test. Due to the small sample size (n = 14) and non-normal data distribution ($P < .05$), non-parametric statistical tests were employed. Group differences were evaluated using the Kruskal–Wallis test, and where applicable, Dunn's post-hoc test with Bonferroni correction was applied to account for multiple comparisons. A p-value < .05 was considered statistically significant. Additionally, Spearman's rank correlation was used to examine the relationship between ΔZ_{15kh} and ΔBP-sys. Data visualization was performed using the matplotlib and seaborn libraries.

RESULTS

Patient Characteristics

This study included 14 pediatric patients undergoing maintenance hemodialysis (6 males, 8 females) with a mean age of 9.4 ± 3.9 years. The mean height was 115.6 ± 15.8 cm and the mean weight 34.9 ± 11.3 kg, which is consistent with pediatric dialysis growth patterns. Bioimpedance was measured at the calf using 15 kHz and 150 kHz frequencies before and after each dialysis session. Pre-dialysis systolic and diastolic blood pressures were 111.5 ± 19.2 mmHg and 73.2 ± 21.3 mmHg, respectively, decreasing to 108.3 ± 12.7 mmHg and 69.4 ± 15.1 mmHg post-dialysis. The corresponding percentage changes were −1.75 ± 9.34% for systolic and −2.6 ± 13.8% for diastolic pressure. Serum sodium significantly increased from 137.7 ± 1.0 mmol/L to 140.3 ± 1.3 mmol/L ($P < .001$), with a mean relative increase of 1.9 ± 0.8%. The average ultrafiltration (UF) volume was 1100 ± 300 mL.

Table 1. Dialysis Parameters and Impedance Changes in Pediatric Hemodialysis Patients.

Patient	UF	Na		BP Blood pressure		Impedance Change ΔZ (%) $\Delta Z = z_{post} - z_{pre}$		15khz impedance Na compensated
	UF (lit)	Na Before mmol/L	Na After mmol/L	BP Before	BP After (%)	ΔZ_{15KHZ} (%)	(%)	ΔZ_{15KHZ} (%)
1	1.1	136	140	127/97	2.3/3	-1.28	0.5	1.2
2	1	138	142	85/50	3.5/6	-9.11	3.12	-6.7
3	1	138	139	128/80	-7.8/-15	3.04	2.40	4.07
4	1	136	139	110/62	-4.5/-3.2	-1.21	3.43	0.8
5	0.8	138	140	117/83	6.8/4.8	1.47	0.7	2.1
6	1	138	139	120/80	-1.6/2.5	5.33	1.68	6.2
7	0.8	137	140	90/60	7.7/6.6	3.74	6.77	6.23
8	1.4	138	141	162/124	-29/-36	1.76	3.40	3.73
9	2	140	141	123/90	-3.2/-8	13.6	10.7	14.01
10	1.1	138	143	106/61	0/-6.5	14.6	14.4	18.6
11	1.5	136	139	103/82	2.9/-11	-3.1	-14.7	-1.02
12	0.4	138	140	96/45	-3.1/2.2	4.8	4	6.2
13	1	139	141	99/53	-9/-7.5	9.8	7.8	11.4
14	1.5	138	142	96/55	10.4/29	-19	-22.3	-17
Mean ± SD	1.1 ± 0.3	137.7 ± 1	140.3 ± 1.3	111.5 ± 19.2/ 73.2 ± 21.3	-1.75 ± 9.34/ -2.6 ± 13.8	1.7 ± 8.4	2.8 ± 8.2	

Summary of patient data, including ultrafiltration (UF) volume, pre- and post-dialysis weight, serum sodium levels (Na), blood pressure (BP), and percentage changes in impedance at 15 kHz (ΔZ_{15kHz}) and 150 kHz (ΔZ_{150kHz}) frequencies. The final row displays mean ± standard deviation values for each parameter.

Impedance changes were 1.7 ± 8.4% at 15 kHz and 2.8 ± 8.2% at 150 kHz, reflecting modifications in extracellular and total body water. A full summary of dialysis parameters and individual impedance values is presented in Table 1.

Impedance Ratio Classification

Patients were stratified into three groups based on the impedance ratio (ΔZ_{15kh} / ΔZ_{150kh}):

Group 1: ratio > 1 (n = 7)

Group 2: 0 < ratio < 1 (n = 2)

Group 3: $\Delta Z_{15kh} < 0$ (n = 5)

As shown in Figure 2, Group 1 patients exhibited larger impedance increases at 15 kHz than at 150 kHz, indicative of greater ECW reduction relative to TBW. Group 2 showed minimal ECW changes, and Group 3 presented with negative ΔZ_{15kh} values, implying a paradoxical post-dialysis reduction in impedance, potentially due to sodium accumulation or redistribution.

Mean impedance values for each group were:

Group 1: ΔZ_{15kh} = 5.86 ± 5.9%, ΔZ_{150kh} = 6.70 ± 4.8%

Group 2: ΔZ_{15kh} = 0.095 ± 1.9%, ΔZ_{150kh} = 0.60 ± 0.14%

Group 3: ΔZ_{15kh} = –3.35 ± 8.8%, ΔZ_{150kh} = –5.23 ± 11.2%

Physiological Parameter Changes

Figure 3 presents a boxplot of physiological changes, including systolic and diastolic blood pressures (ΔBP-sys, ΔBP-dia) and serum sodium (ΔNa), across the three patient groups defined by the impedance ratio (ΔZ_{15kh} / ΔZ_{150kh}), demonstrating distinct physiological profiles for each cluster that align with the impedance-based grouping.

Systolic Blood Pressure Changes (ΔBP-sys). In Group 1 (n = 7), the median ΔBP-sys was -3.2% (IQR: -7.8 to 0.0), with mean pre-dialysis BP of 112.7/70.3 mmHg (systolic/diastolic) and post-dialysis BP of 109.9/67.6 mmHg. Group 2 (n = 2) displayed a median ΔBP-sys of -10.7% (IQR: -29.0 to 7.7), with mean pre-dialysis BP of 126.0/92.0 mmHg and post-dialysis BP of 106.0/72.0 mmHg. Group 3 (n = 5) showed a median ΔBP-sys of 2.9% (IQR: 2.3 to 10.4), with mean pre-dialysis BP of 104.2/69.2 mmHg and post-dialysis BP of 107.0/71.4 mmHg. Kruskal-Wallis analysis revealed significant differences across groups (H = 6.82, *P* = .033). Post-hoc Dunn's tests with Bonferroni correction confirmed significant differences between Group 1 and Group 2 (*P* = .045) and between Group 1 and Group 3 (*P* = .028), but not between Group 2 and Group 3 (*P* = .092) (raw data in Table 1).

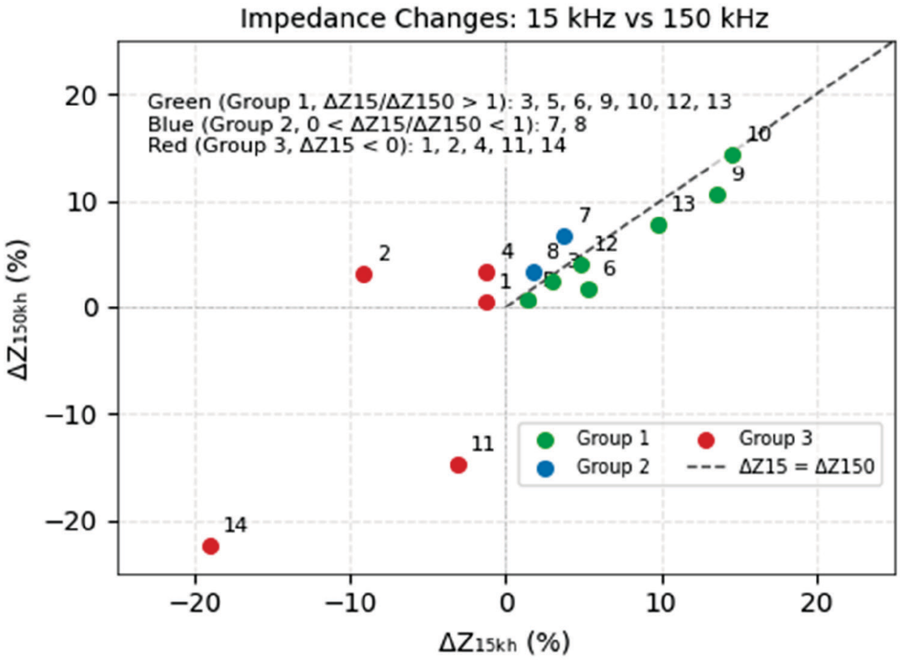

Figure 2. Impedance Changes at 15 kHz vs. 150 kHz in Dialysis Patients.
Scatter plot illustrating the relationship between percentage changes in bioimpedance at 15 kHz (ΔZ_{15kHz}) and 150 kHz (ΔZ_{150kHz}) for 14 dialysis patients. Patients are classified into three groups based on the ratio of $\Delta Z_{15kHz}/\Delta Z_{150kHz}$: Group 1 (green, ratio > 1), Group 2 (blue, 0 < ratio < 1), and Group 3 (red, ΔZ_{15kHz} < 0). The dashed line represents $\Delta Z_{15kHz} = \Delta Z1_{50kHz}$ in the positive quadrant. Patient numbers are annotated next to each data point, with group assignments listed in the top-left corner.

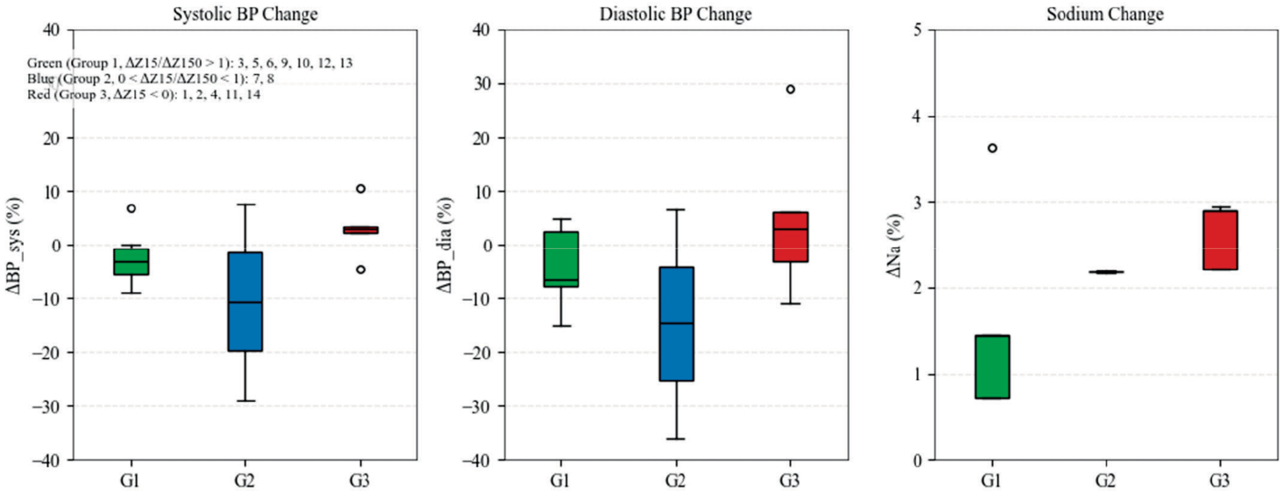

Figure 3. Boxplot of Physiological Changes by Patient Groups.
Boxplots show percentage changes in systolic blood pressure (ΔBP_sys, left), diastolic blood pressure (ΔBP_dia, middle), and sodium concentration (ΔNa, right) for three groups based on impedance ratio ($\Delta Z_{15}/\Delta Z_{150}$). Group 1 (green, $\Delta Z_{15}/\Delta Z_{150} > 1$: patients 3, 5, 6, 9, 10, 12, 13), Group 2 (blue, $0 < \Delta Z_{15}/\Delta Z_{150} < 1$: patients 7, 8), and Group 3 (red, $\Delta Z_{15} < 0$: patients 1, 2, 4, 11, 14). Medians, interquartile ranges, whiskers, and outliers are depicted. Groups 1 and 3 show greater variability in ΔBP_sys and ΔBP_dia; ΔNa distributions are tighter.

Diastolic Blood Pressure Changes (ΔBP-dia). For Group 1 (n = 7), the median ΔBP-dia was -6.5% (IQR: -8 to 2.5), for Group 2 (n = 2) it was -14.7% (range: -36 to 6.6), and for Group 3 (n = 5) it was 3% (IQR: -7.1 to 17.5). Significant differences were observed across groups (Kruskal-Wallis test, H = 7.45, $P = .024$). Post-hoc Dunn's tests with Bonferroni correction indicated significant differences between Group 1 and Group 2 ($P = .036$) and between Group 1 and Group 3 ($P = .019$), but not between Group 2 and Group 3 ($P = .075$) (raw data in Table 1).

Serum Sodium Changes (ΔNa). Group 1 (n = 7) displayed a median ΔNa of 1.44% (IQR: 0.72 to 1.45), Group 2 (n = 2) a median of 2.18% (IQR: 2.17 to 2.19), and Group 3 (n = 5) a median of 2.90% (IQR: 2.21 to 2.94). Kruskal-Wallis analysis confirmed significant differences across groups (H = 6.12, $P = .047$). Post-hoc Dunn's tests with Bonferroni correction revealed a significant difference between Group 1 and Group 3 ($P = .042$), but not between Group 1 and Group 2 ($P = .063$) or Group 2 and Group 3 ($P = .089$) (raw data in Table 1). These findings underscore the effectiveness of the impedance ratio in clustering patients based on their physiological responses.

Relationship Between Impedance and Physiological Parameters

Figure 4 illustrates the relationship between changes in impedance at 15 kHz (ΔZ_{15kh}), reflecting extracellular water (ECW) shifts, and percentage changes in systolic blood pressure (ΔBP-sys), diastolic blood pressure (ΔBP-dia), and serum sodium (ΔNa) across the three patient groups classified by the impedance ratio (ΔZ_{15kh} / ΔZ_{150kh}). In the ΔZ_{15kh} vs. ΔBP-sys plot, Group 1 (n = 7) showed ΔZ_{15kh} from 0% to 15% with ΔBP-sys from -10% to 0% (e.g., Patients 3, 10), Group 2 (n = 2) exhibited ΔZ_{15kh} from 0% to 1.76% with ΔBP-sys from -29% to 7.7% (e.g., Patient 8), and Group 3 (n = 5) displayed ΔZ_{15kh} from -19% to -10% with ΔBP-sys from 0% to 10.4% (e.g., Patient 14). In the ΔZ_{15kh} vs. ΔBP-dia plot, Group 1 ranged from 0% to 15% ΔZ_{1h5kh} with ΔBP-dia from 10% to 10%, Group 2 showed ΔZ_{15kh} from 0% to 1.76% with ΔBP-dia from -36% to 6.6% (e.g., Patient 8), and Group 3 exhibited ΔZ_{1h5kh} from -19% to -10% with ΔBP-dia from 0% to 29% (e.g., Patient 14). In the ΔZ_{15kh} vs. ΔNa plot, Group 1 ranged from 0% to 15% ΔZ_{15kh} with ΔNa from 0% to 1.45%, Group 2 showed ΔZ_{15kh} from 0% to 1.76% with ΔNa from 2.17% to 2.19%, and Group 3 exhibited ΔZ_{1h5kh} from -19% to -10% with ΔNa from 2.21% to 2.9% (e.g., Patients 2, 14), with a threshold at ΔNa = 2.2%. A positive correlation was observed between ΔZ_{15kh} and ΔBP-sys using Spearman's rank correlation test (r = 0.650, $P = .012$), indicating a significant relationship, particularly evident in Group 3 where patients with negative ΔZ_{15kh} values showed increased ΔBP-sys. In contrast, no significant correlations were found for ΔZ_{15kh} with ΔBP-dia

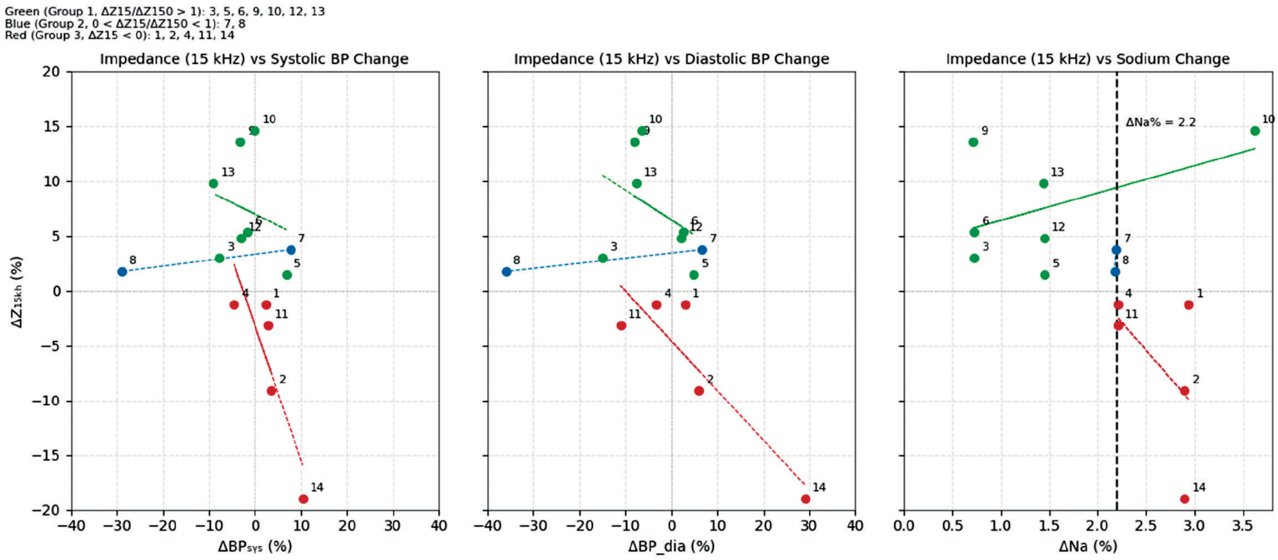

Figure 4. Relationship Between Impedance Changes at 15 kHz and Physiological Parameters in Dialysis Patients.
This figure presents scatter plots of percentage changes in systolic blood pressure (ΔBP_sys, left), diastolic blood pressure (ΔBP_dia, center), and serum sodium (ΔNa%, right) versus percentage changes in bioimpedance at 15 kHz (ΔZ_{15kHz}) for 14 dialysis patients. Patients are classified into three groups based on the ratio of impedance changes ($\Delta Z_{15kHz}/\Delta Z_{150kHz}$): Group 1 (green, ratio > 1), Group 2 (blue, 0 < ratio < 1), and Group 3 (red, ΔZ_{15kHz} < 0). Each point is labeled with the patient number, and regression lines are shown for each group. A vertical line at ΔNa% = 2.2 is highlighted in the sodium subplot. Group assignments are listed in the top-left corner of the figure.

(r = 0.12, *P* = .68) or ΔNa (r = 0.25, *P* = .39).

DISCUSSION

This study applied the impedance ratio ($\frac{\Delta Z_{15kh}}{\Delta Z_{150kh}}$) to stratify pediatric hemodialysis patients and evaluate fluid distribution dynamics, revealing three distinct physiological response profiles with potential implications for individualized fluid management. Under standard dialysis conditions, both extracellular water (ECW) and total body water (TBW) are expected to decrease, with impedance increasing accordingly. Because 15 kHz current primarily reflects ECW and 150 kHz encompasses both ECW and intracellular water, a greater post-dialysis increase in impedance is typically observed at 15 kHz. However, deviations from this expected pattern may occur due to two key mechanisms, both closely linked to sodium balance. First, sodium-induced osmotic shifts can promote the movement of fluid from the intracellular to the extracellular compartment, resulting in an increase in ECW without a net loss in total fluid volume. Second, elevated extracellular sodium levels enhance tissue conductivity, thereby lowering measured impedance even in the absence of fluid accumulation. These factors can obscure the relationship between impedance and actual hydration status, complicating interpretation. The impedance ratio, by capturing the relative changes in ECW and TBW, serves as a sensitive index to detect such non-typical responses. This approach offers novel insight into the dynamic and multifactorial nature of fluid regulation during dialysis, particularly in pediatric patients with variable sodium handling. Accordingly, impedance-based classification may aid in tailoring dialysate composition and ultrafiltration targets to better manage volume status and preserve hemodynamic stability.

Group 1: Optimal Fluid Removal (n = 7)

Group 1 (ΔZ_{15kh} / ΔZ_{150kh} > 1, n = 7) demonstrated a marked post-dialysis reduction in extracellular water (ECW) relative to total body water (TBW), aligning with the expected physiological response during conventional hemodialysis. The mean impedance changes at 15 kHz (ΔZ_{15kh}), which reflects ECW, was 7.99% (range: 1.47% to 14.6%), accompanied by a moderate decline in systolic blood pressure (median ΔBP-sys = –3.1%). These findings indicate effective extracellular fluid removal with preserved hemodynamic stability. The ultrafiltration (UF) volume in this group averaged 1.1 ± 0.3 liters, and no signs of intradialytic hypotension were observed, suggesting that fluid removal was both efficient and well tolerated. The dialysate sodium concentration of 143 mEq/L likely contributed to osmotic support and plasma refilling, minimizing vascular instability. Collectively, this group represents the target outcome for hemodialysis treatment: successful ECW reduction under balanced sodium and UF conditions.

In Group 3 ($\Delta Z_{15kh} < 0$, n = 5), a paradoxical reduction in post-dialysis impedance was observed, with ΔZ_{15kh} values ranging from –19% to –1.21% despite net fluid removal. This phenomenon is likely driven by a combination of elevated extracellular sodium concentrations and concurrent expansion of extracellular water (ECW). Serum sodium levels increased by up to 5% in this group, and four out of five patients exhibited a rise in systolic blood pressure (ΔBP-sys: –4.5% to 10.4%), with variable diastolic changes (ΔBP-dia: –11% to 29%). These findings suggest that sodium-induced osmotic shifts facilitated fluid redistribution into the extracellular compartment, increasing tissue conductivity and thereby reducing impedance. A significant positive correlation between ΔZ_{15kh} and ΔBP-sys (Spearman's r = 0.650, $P = .012$) further supports the hypothesis that sodium-driven ECW expansion contributes to both impedance reduction and hemodynamic alterations. These results highlight the need for personalized dialysate sodium strategies—potentially involving concentrations below 143 mEq/L—to minimize fluid overload and maintain cardiovascular stability in susceptible patients.

Group 2 ($0 < \Delta Z_{15kh} / \Delta Z_{150kh} < 1$, n = 2) included two patients who exhibited modest changes in extracellular water impedance (ΔZ_{15kh}: 1.76% to 3.74%) despite undergoing ultrafiltration. This limited ECW response occurred alongside divergent blood pressure outcomes (ΔBP-sys: –29% to 7.7%; ΔBP-dia: –36% to 6.6%), suggesting individualized fluid dynamics influenced by sodium handling. In patient 8, a substantial drop in systolic blood pressure (ΔBP-sys = –29%) was accompanied by an initial ΔZ_{15kh} of 1.76%. After correcting for sodium concentration (increase from 138 to 141 mmol/L following 1.4 L UF), the adjusted ΔZ_{15kh} rose to 3.73%, exceeding ΔZ_{150kh} (3.40%), indicating a physiological pattern more consistent with Group 1. This suggests that elevated sodium enhanced tissue conductivity, artificially lowering the uncorrected impedance change. In contrast, Patient 7 showed a slight rise in systolic blood pressure (ΔBP-sys = 7.7%) and minimal ECW impedance change (ΔZ_{15kh} = 3.74%) despite a low UF volume (0.8 L). This pattern may reflect sodium-driven extracellular fluid expansion (Na increased from 137 to 140 mmol/L), leading to reduced impedance despite minimal actual fluid removal.

Collectively, these findings suggest that sodium-induced osmotic redistribution, rather than true volume depletion, predominated in group 2. This underscores the potential limitations of standard ultrafiltration targets in detecting and managing atypical fluid responses, highlighting the need for individualized strategies such as sodium-adjusted dialysis prescriptions in selected patients.

Statistical analysis confirmed significant differences among the groups in systolic pressure changes (ΔBP-sys, H = 6.82, $P = .033$), diastolic pressure changes (ΔBP-dia, H = 7.45, $P = .024$), and sodium shifts (ΔNa, H = 6.12, $P = .047$), reinforcing the clinical relevance of the impedance ratio in detecting nuanced fluid responses during dialysis.

Conventional bioimpedance indices, such as the extracellular water to total body water ratio (ECW/TBW) and the overhydration to extracellular water ratio (OH/ECW), are primarily designed to assess static hydration status in dialysis patients and are widely utilized for long-term risk stratification. Established thresholds, including ECW/TBW > 0.40 and OH/ECW > 0.15, have been validated as predictors of increased mortality risk, with studies demonstrating their association with adverse outcomes through survival analyses and receiver operating characteristic (ROC) curves.[21,22] However, these indices are ill-suited for monitoring dynamic fluid shifts during dialysis sessions, as their underlying algorithms are calibrated for healthy adults and fail to account for the complex fluid distribution and sodium variability observed in pediatric patients. It has been reported that a 20% increase in tissue sodium can lead to an overestimation of ECW by 1.2–2.4 L,[23] while ultrafiltration estimation errors using these methods can exceed 50% in patients with atypical fluid dynamics.[21] Such limitations underscore the inadequacy of ECW/TBW and OH/ECW for real-time fluid management. In contrast, our approach, employing the impedance ratio ($\Delta Z_{15kh} / \Delta Z_{150kh}$) based on relative impedance changes at 15 kHz (sensitive to ECW) and 150 kHz (sensitive to TBW), offers a more robust and sensitive tool for capturing dynamic fluid alterations during hemodialysis, circumventing the volume conversion errors inherent in conventional indices.

Limitation

This study has several limitations that warrant consideration. First, the sample size was relatively small (n = 14), which limits statistical power and generalizability—a common challenge in pediatric dialysis research due to low patient availability. Second, impedance measurements are inherently sensitive to technical factors such as electrode placement, skin integrity, and patient movement. These sources of variability are particularly relevant in dialysis settings where fluid shifts are subtle. Finally, this study did not include long-term follow-up or direct comparison with standard hydration assessment methods such as whole-body bioimpedance analysis (BIA) or clinical dry weight estimation. These limitations highlight the need for further validation in larger and more diverse patient cohorts.

CONCLUSION

This study demonstrated the potential utility of the impedance ratio (ΔZ_{15kh} / ΔZ_{150kh}) as a physiological index for classifying pediatric hemodialysis patients according to fluid redistribution patterns. Using a dialysate sodium concentration of 143 mEq/L, the results highlighted distinct impedance responses related to sodium-induced shifts and hemodynamic stability.

Tailoring dialysate sodium and ultrafiltration (UF) rates to achieve impedance patterns consistent with effective extracellular fluid removal may help improve volume control and reduce post-dialysis hypertension. Although preliminary, these findings suggest that impedance-based assessment could support individualized dialysis prescriptions and enhance physiological stability.

Further studies with larger and more diverse cohorts are warranted to validate this approach and examine the impact of alternative sodium concentrations on clinical outcomes.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest

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*Correspondence to:
Mohammad Firouzmand, MD
sh.Ehsani Rad St., Enqelab St., Ahmadabad Mostoufi Rd., Azadegan Highway, P.O.Box 33535-111, Tehran 3313193685, I. R. Iran
Tel : 09124144272
E-mail: firouzmand@irost.org

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