sciendo | Journal of Electrical Bioimpedance | JoEB bioimpedance.net

J Electr Bioimp, vol. 10, pp. 55-62, 2019
Received 25 Mar 2019 / published 15 Aug 2019
https://doi.org/10.2478/joeb-2019-0008

Knee-to-knee bioimpedance measurements to monitor changes in extracellular fluid in haemodynamic-unstable patients during dialysis

Abdul Hamid Ismail [1,3], Georg Schlieper [2], Marian Walter [1], Jürgen Floege [2], and Steffen Leonhardt [1]

1. *Chair for Medical Information Technology, Helmholtz Institute, RWTH Aachen University, Pauwelsstr. 20, Aachen, Germany*
2. *Department of Nephrology and Immunology (Medical Clinic II), RWTH Aachen University Hospital, Pauwelsstr. 30, Aachen, Germany*
3. *E-mail any correspondence to: ismail@hia.rwth-aachen.de*

Abstract
The feasibility of bioimpedance spectroscopy (BIS) techniques for monitoring intradialytic changes in body fluids is advancing. The aim of this study was to compare the knee-to-knee (kkBIS) with the traditional whole-body (whBIS) with respect to continuous assessment of fluid volume status in hemodialysis patients. Twenty patients divided into two groups, hemodynamically stable and unstable, were recruited. Bioimpedance data from two different electrodes configurations (hand-to-foot and knee-to-knee) were collected and retrospectively analysed. A good correlation between the two methods with respect to changes in extracellular resistance (R_e) and R_e normalized for ultrafiltration volume (ΔR_e/UFV) with $p < 0.001$ was observed. The relationship between relative change (%) in ΔR_e and that in patient weight was most notable with kkBIS (4.82 ± 3.31 %/kg) in comparison to whBIS (3.69 ± 2.90 %/kg) in unstable patients. Furthermore, results based on kkBIS showed a reduced ability of the thigh compartments to keep up with the volume changes in the trunk for unstable patients. kkBIS provided a comparable sensitivity to whBIS even in patients at risk of intradialytic hypotension while avoiding the need for the complex implementation imposed by whBIS or other configurations.

Keywords: Bioimpedance; hemodialysis; intradialytic hypotension

Introduction
Over the last few decades, continuous advances in dialysis technologies have increased the safety and efficacy of hemodialysis (HD) [1]. At present, many of the common acute complications during HD are related to fluid status and impaired compensatory mechanisms. In particular, the accuracy to measure changes in intradialytic fluid status and to assess the fluid overload remains a problem. Inaccuracy might result in excessive volume depletion during treatment, and possibly, the development of intradialytic hypotension (IDH) due to excess drop in systolic blood pressure. IDH increases patient morbidity (e.g. via nausea, vomiting, headaches and muscle cramps), reduces treatment efficacy, and increases the risk of mortality [2].

In recent years, multi-frequency bioimpedance spectroscopy (BIS) techniques have become more clinically attractive as they enable non-invasive, simple, and relatively inexpensive tools to assess continuously the fluid status during HD [3]. A high level of accuracy for whole-body BIS (whBIS) compared with gold standards (e.g. dilution methods) have been reported in literature [4,5]. As the accuracy and reproducibility of whBIS can be influenced by external factors, such as changes in body position, the sum of segmental BIS bioimpedance (sBIS) technique was introduced [6,7]. Yet, the application of whBIS or sBIS for routine clinical use is sometimes impractical, as it requires a relatively complex implementation. Patients have to be motionless in a fixed position with arms and legs extended during the whole treatment and extra cables and electrodes are required. This is uncomfortable for many patients and costly, especially as it requires continuous surveillance to ensure intraindividual reproducibility. Moreover, correct placement of electrodes can sometimes be difficult due to the dialysis fistula or other medical conditions. As extremities account for up to 88% of the total body impedance [8], alternative configuration of BIS, namely knee-to-knee BIS (kkBIS) [9] was introduced. This new configuration should be reliable for continuous applications while avoiding the need for complex setups as required for whBIS or sBIS. To our knowledge, the adequacy of kkBIS so far has only been assessed in hemodynamically stable patients.

This study aimed at comparing the adequacy of kkBIS with whBIS in respect to continuous monitoring of extracellular fluid volume in hemodynamically unstable HD patients, and the usefulness of kkBIS for detecting the patient's risk of IDH. The correlation between whBIS and kkBIS on the basis of changes in absolute extracellular resistance (R_e) and R_e normalized for ultrafiltration volume (ΔR_e/UFV) has been investigated. Finally, volume calculations from both methods were compared and their cumulative changes were investigated against collected ultrafiltrate.

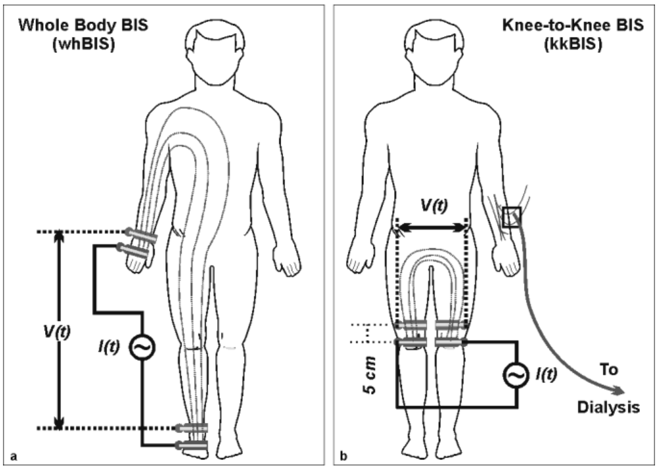

Fig.1: Position of the electrodes for (a) the whole-body BIS (whBIS) and (b) knee-to-knee BIS (kkBIS) measurements. Four electrodes were used for each of the BIS methods, i.e. two for current injection I(t) and two for voltage sensing V(t).

Materials and methods

Subjects

Twenty HD patients (13 males and 7 females; mean ages 62 ± 16 years) were studied twice in the dialysis unit of the Department of Nephrology, RWTH Aachen University Hospital. All patients underwent HD for four hours with a fixed ultrafiltration rate of 560 ± 265 ml/h and a dialysate fluid composition of 138 mmol/L sodium (Na^+), 2.1 ± 0.6 mmol/L potassium (K^+), 1.25 mmol/L calcium (Ca^{2+}), 5.5 mmol/L glucose (Glu), and 32 mmol/L bicarbonate (HCO_3^-). The ultrafiltration rate was only changed if required for clinical reasons. The inclusion criteria were: in- and outpatients ≥ 18 years of age on chronic HD three times a week, who had been on dialysis for a minimum of six months. The exclusion criteria were HIV or hepatitis virus C infection, pregnancy, pacemakers, amputation of a limb, artificial joints, or receiving a blood transfusion within a week before the measurement.

Measurements

Obtained measurements included the patient's pre- and post-dialysis weight, height, thigh length and circumferences, systolic and diastolic blood pressure, ultrafiltration rate and volume (UFV), plasma electrolytes, and BIS measurements.

Bioimpedance measurements were obtained using a multi-frequency bioimpedance device (Xitron Hydra 4200, Xitron Technologies Inc., San Diego, CA, USA) and standard hydrogel-aluminium BIS electrodes placed on the non-dialysis access side of the patient according to the manufacturer's instruction as given in Fig. 1. For whBIS measurement, the position of the electrodes was chosen according to the manufacturer's instruction, while for kkBIS, a distance of 5 cm was always kept between the voltage and current electrodes to ensure reproducibility of the measurement. Impedance data for kkBIS and whBIS were recorded sequentially with an interval of less than one minute between the two measurements.

Extracellular resistance (R_e) for each BIS method were extracted by fitting the measured impedance data to the Cole model [10], while total body extracellular fluid (ECF_{whBIS}) was calculated as described elsewhere [11,12]. Knee-to-knee extracellular fluid was calculated according to either Matthie [13] and Medrano *et al.* [14] (ECF_{kkBIS}), or as described elsewhere in [15,16] ($ECF_{kkBIS,Z}$).

Blood samples were drawn from the arterial line and analyzed using an automated benchtop blood gas analyzer (ABL800 Basic, Radiometer Medical ApS, Brønshøj, Denmark) for plasma electrolytes and glucose concentrations. Systolic and diastolic blood pressures were measured using the blood pressure monitor integrated in the dialysis machine. All measurements were recorded every 30 min in the supine position with patients resting on a bed with their legs apart and arms placed away from the body.

Study Protocol and Data Analysis

Patients were post-dialytically divided into a hemodynamiccally stable group, which included patients with a stable systolic blood pressure throughout HD (drop < 25 mmHg), whereas the unstable group included patients with a continuous symptomatic drop in systolic blood pressure of ≥ 25 mmHg. For this study, the clinical symptoms considered relevant in the context of IDH were diaphoresis, nausea, vomiting, edema, cramps, blurred vision, presyncope, headache, and fatigue. Medical interventions such as fluid infusion, switching off ultrafiltration, and/or raising of the patient's legs were applied as necessary.

The difference between the groups at baseline was tested by Student's t-test or Pearson's Chi-square test, as appropriate. Regression analysis was applied to study the agreement between the whBIS and kkBIS method, and to assess the correlation between the pre- and post-dialytic changes in R_e and patient's weight for both methods. For comparison between the patient groups, relative changes in extracellular resistance normalized for the UFV (ΔR_e/UFV in [%/L]) were used. In all analyses, a p value ≤ 0.05 was considered statistically significant.

Table 1 Pre-dialysis physical and clinical characteristics. Data are means ± SD from 20 patients (40 measurements).

Baseline Characteristics	Hemodialysis patients		
	Stable (n = 10)	Unstable (n = 10)	***p***
Gender, % female	20.0	50.0	0.350
Age, years	63.3 ± 15.8	60.7 ± 16.4	0.722
Height, cm	174.7 ± 7.9	165.8 ± 9.0	**0.030**
Weight, kg	83.6 ± 8.3	69.5 ± 17.3	**0.038**
BMI, Kg / m^2	27.5 ± 3.4	25.4 ± 6.8	0.398
Dialysis duration, min	234.0 ± 19.0	222.0 ± 29.0	0.290
Ultrafiltration Rate, ml / h	557.5 ± 305.7	564.2 ± 235.1	0.957
UFV, mL	2252.0 ± 1226.9	2300.0 ± 1091.4	0.927
SysBP, mmHg	123.7 ± 17.2	125.4 ± 19.1	0.836
DiaBP, mmHf	71.5 ± 14.6	64.1 ± 11.6	0.226
ECF_{whBIS}, L	21.6 ± 2.4	17.3 ± 3.9	**0.009**
ECF_{kkBIS}, L	2.7 ± 0.5	2.6 ± 0.7	0.769
Body temperature, °C	36.0 ± 0.6	35.9 ± 0.4	0.688
O_2 saturation, %	96.9 ± 2.4	96.6 ± 2.7	0.796
Plasma Na^+, mmol / L	136.8 ± 2.1	136.7 ± 2.7	0.928
Plasma K^+, mmol / L	4.4 ± 0.7	4.7 ± 1.0	0.530
Plasma ionized Ca^{2+}, mmol / L	1.1 ± 0.1	1.1 ± 0.1	0.461
Plasma glucose, mmol / L	121.4 ± 27.8	124.6 ± 31.3	0.809

BMI: body mass index, UFV: ultrafiltration volume, SysBP: systolic blood pressure, DiaBP: diastolic blood pressure, ECF: extracellular fluid.

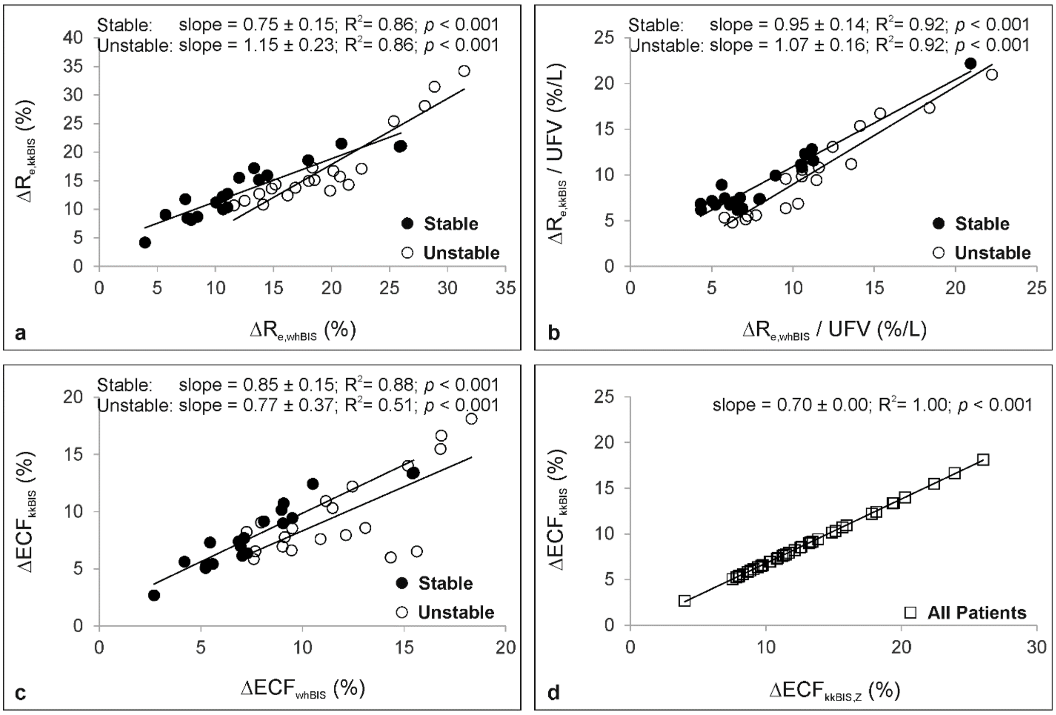

Fig.2: Relationship of relative changes in different BIS parameters estimated on basis of pre-HD and post-HD values from kkBIS and whBIS methods. The relative changes were calculated as (|pre-HD – post-HD|)/pre-HD x 100 for (a) ΔR_e (%), (b) ΔR_e/UFV (%/L), (c) ΔECF (%) and (d) ΔECF (%) according to [15, 16]. Each patient has two entries.

Informed consent

Informed consent has been obtained from all individuals included in this study.

Ethical approval

The research related to human use has been complied with all relevant national regulations, institutional policies and in accordance with the tenets of the Helsinki Declaration, and has been approved by the local medical ethics committee.

Results

The mean age of the patients was 62 ± 16 years with a body height of 170 ± 9 cm and 35% of patients being female. Twenty patients each were categorized as stable or unstable during HD. Table 1 summarizes the baseline clinical characteristics of the study population and their treatments. Apart from the whole-body extracellular volume ECF_{whBIS} ($p = 0.009$), there was no significant differences between the groups at baseline with regard to their clinical characteristics and dialysis settings (Table 1) or composition of dialysate fluid (data not shown). If ECF_{whBIS} were to be normalized to baseline patient's weight, no significant difference could be observed ($p = 0.928$). Baseline thigh's ECF value did not contribute as well to the hemodynamic stability of the patient with $p = 0.769$, or if normalized to weight, with $p = 0.200$.

Clinical and physical assessment of the patients revealed that 35% of the patients showed signs of pre-dialysis overhydration mainly in the thigh and lower leg with a mean systolic blood pressure of 135 ± 9.6 mmHg. Intradialytic mean weight loss was 2.1 ± 1.0 kg in the stable group and 1.8 ± 0.9 kg in unstable patients ($p = 0.499$). Systolic pressure decreased by 14.8 ± 9.5 mmHg in stable and by 20.1 ± 14.8 mmHg in unstable patients ($p = 0.356$).

The correlation of relative changes in ΔR_e and in ΔR_e/UFV between the whBIS and kkBIS method is given in Fig. 2(a-b). Intradialytic changes in ΔR_e (%) correlated very well between the methods ($R^2 = 0.86$, $p < 0.001$) for both groups. If normalized for UFV, the correlation was slightly improved to $R^2 = 0.92$, $p < 0.001$. Loss in the thigh's extracellular fluid (ECF_{kkBIS}) also correlated with the total body loss in ECF ($R^2 = 0.88$, $p < 0.001$) for stable patients and to a lesser extent ($R^2 = 0.51$, $p < 0.001$) for unstable patients. This correlation persisted, when the thigh ECF was estimated using a specific resistivity value for the legs ($ECF_{kkBIS,z}$). Nevertheless, $ECF_{kkBIS,z}$ values for all patients were slightly higher (0.25 ± 0.17 L) in comparison to those (ECF_{kkBIS}: 0.20 ± 0.07 L) calculated using a fixed resistivity value for the whole body.

The relative change in ΔR_e/UFV in [%/L] during treatment is shown in Fig. 3(a) for kkBIS and in Fig. 3(b) for whBIS; their ratio is presented in Fig. 3(c). The relative changes in thigh and total body ECF with respect to pre-HD values are given in Fig. 3(d). Within the first hour of HD, the loss of thigh ECF_{kkBIS} was 7.7 ± 3.3 % in stable patients compared to 3.5 ± 2.3 % loss of total body ECF. In unstable patients, thigh ECF_{kkBIS} decreased by only 1.8 ± 1.5 % compared to 6.4 ± 2.4 % in total body ECF. Only at the end of HD, the decrease in thigh ECF_{kkBIS} (9.1 ± 3.7 %) approached that of total body ECF (11.1 ± 3.4%) for unstable patients.

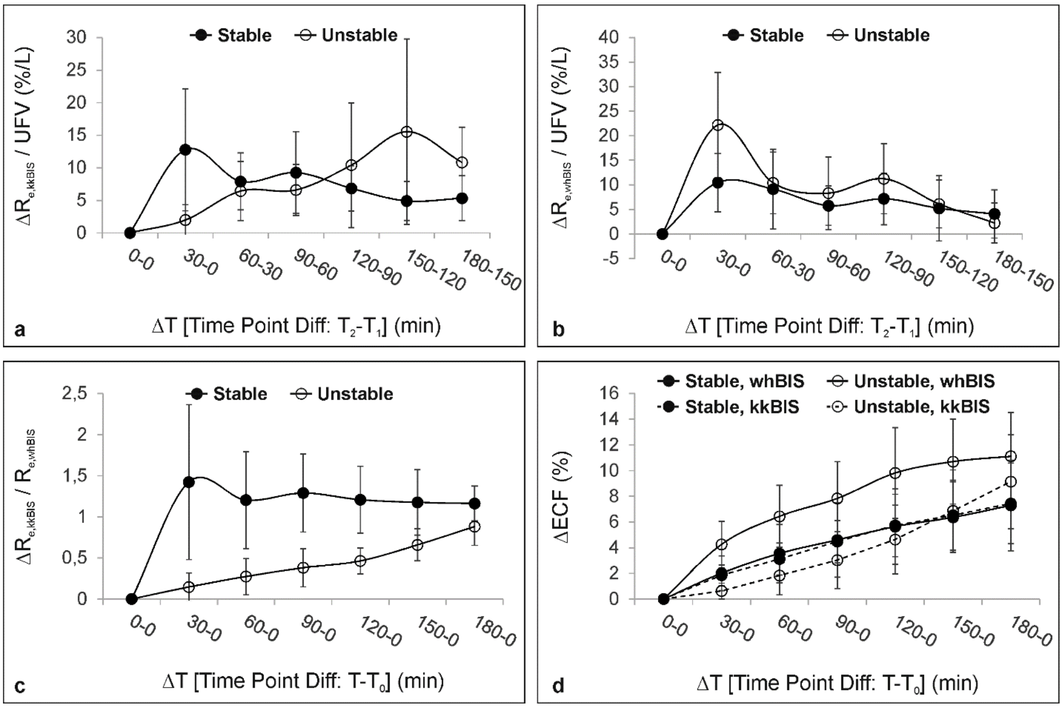

Fig.3: Graphs showing the trends (mean±SD) in the patient groups for (a) relative change in knee-to-knee extracellular resistance ($\Delta R_{e,kkBIS}$), (b) relative change in total body extracellular resistance ($\Delta R_{e,whBSI}$), both normalized by UFV (removed during the corresponding time interval), (c) the ratio of $\Delta R_{e,kkBIS}$ to $\Delta R_{e,whBIS}$, and (d) the relative changes in extracellular fluid (ΔECF, %) measured by kkBIS and whBIS during the time course of the treatment.

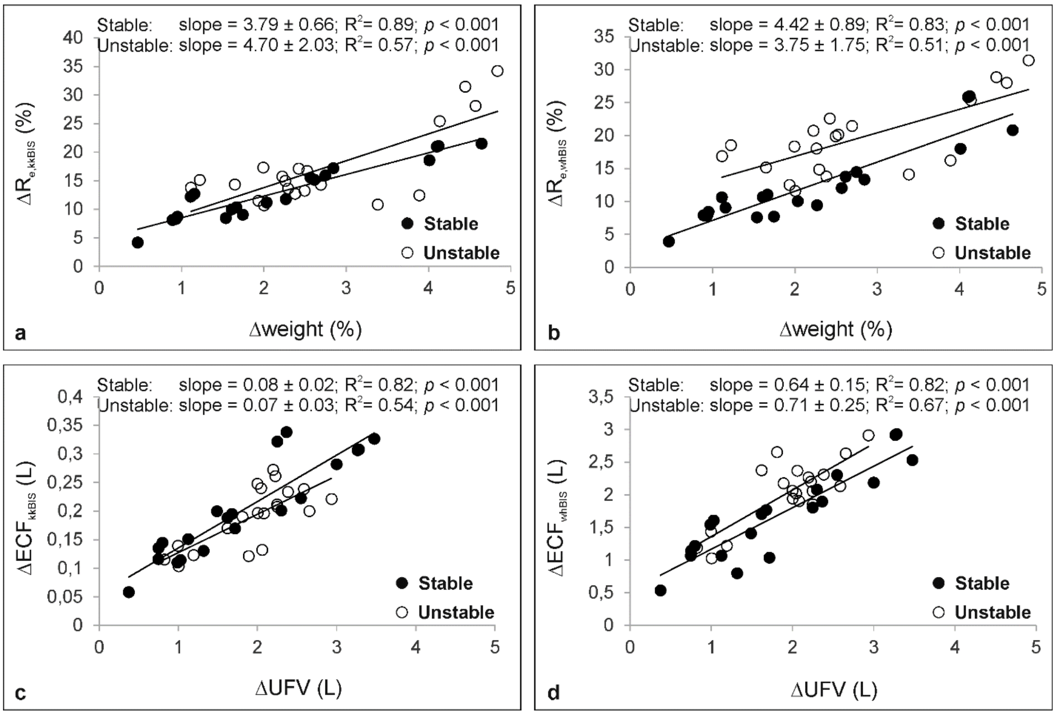

Fig.4: Pre-HD to post-HD comparison of (a-b) relative changes in $R_{e,kkBIS}$ (%) and $R_{e,whBIS}$ (%), respectively, with changes of patient weight (%). Pre-HD to post-HD comparison of (c-d) changes in ΔECF_{kkBIS} (L) or ΔECF_{whBIS} (L), respectively, with cumulative ultrafiltration volume (UFV, L). Each patient has two entries.

Linear regression analysis revealed a good relationship between relative intradialytic weight loss and changes in R_e (for both whBIS and kkBIS), Fig. 4(a-b). Similar results were obtained for ΔECF compared to the collected UFV as shown in Fig. 4(c-d). Nevertheless, data revealed a significantly larger relative change in R_e normalized to wt (pre-HD to post-HD) for unstable patients. Moreover, if we consider the difference in ($\Delta R_{e,whBIS}$ - $\Delta R_{e,kkBIS}$)/Δwt between pre-HD to post-HD, stable patients would be characterized with a significant lower mean difference of 0.51 ± 0.89 compared to 1.1 ± 1.20 for unstable ones (p < 0.001).

Compared to stable patients, the accumulative loss in thigh ECF_{kkBIS} was significantly lower in unstable patients especially within the first hour of the treatment (p = 0.004 after 60 min). Fig. 5(a-b) depicts the accumulative changes in ECF, estimated either from kkBIS or whBIS method, and compared to the accumulative UFV during HD treatments in both patient groups. Fig. 5(c) presents their ratio for both patient groups.

Discussion and conclusion

In the present study, we compared the application of the kkBIS with the standard whBIS method to assess the extracellular fluid status in a cohort of symptomatic unstable versus stable HD patients. kkBIS not only increases the comfort of the patient but was also found to correlate very well with whBIS. Furthermore, the intradialytic changes in parameters (as ΔR_e/UFV and ΔR_e/wt) obtained via kkBIS might be used to identify patients at risk of IDH.

Similar to previous work [17], our data confirms that baseline characteristics do not allow differentiating stable from unstable patients. In order to compare kkBIS with the traditional method whBIS, the first step was to compare the measured intradialytic changes in R_e and R_e normalized to UFV. Regression analysis revealed an excellent correlation between both methods, which is in agreement with the work of Cox-Reijven *et al.* [18]. The next step was to compare the estimated ECF from measured R_e values. Here, lower agreement (R^2 > 0.50) between the methods was observed for the unstable group in particular. This could be due to the model applied to make segmental volume calculations. The estimation of ECF volumes is subject to some uncertainty concerning interpretation of the collected impedance data and a number of simplifications as the use of constant resistivity derived from a healthy population [11, 19]. Nevertheless, it is worth noting that in our study, segmental volume calculations using a specific resistivity value for legs fully correlated with those done using a constant resistivity value for the whole body, Fig. 2(d).

The relative change in extracellular resistance (R_e) normalized to UFV could be another way to identify unstable patients, without being subject to possible inaccuracies arising from calculating ECF volumes, Fig. 3(a-b). This could be of particular interest especially when profiled ultrafiltration rate is applied. The ECF transport rate from legs to the trunk plays a pivotal role in this refilling process [20, 21]. Shulman *et al.* [20] found that legs contributed up to 0.69 L to the change in total body ECF of 1.33 L as measured by whBIS during 18 dialysis sessions with a mean UFV of 2.0 L, while the trunk contributed only 0.17 L. Others observed that during HD, major changes in total body extracellular resistance localized to the legs as compared to the arms and torso [7, 22, 23]. Fig. 3(c) partially reflects the contribution from the upper parts of the legs (thighs) to the total changes in R_e. The lower ratios of $\Delta R_{e,kkBIS}/\Delta R_{e,whBIS}$ for unstable patients, compared with stable patients, may indicate a reduced ability of the leg compartments to keep up with the volume changes in the trunk, possibly leading to a significant reduction in blood volume and, thus, to development of IDH, Fig. 3(d). Only later during dialysis, this ratio starts to catch up with that of stable patients possibly due to clinical intervention. If relative changes in ECF with respect to pre-HD values were considered, a similar observation held true. In stable patients, the losses of ECF_{kkBIS} from leg compartments followed those of the whole-body with an equivalent slope throughout the treatment. On the other hand, fluid losses from the lower extremities fell significantly behind those observed from whole-body measurements for unstable patients. In the present study, the rapid change in knee-to-knee $R_{e,kkBIS}$ within the first hour of treatment was followed by a slower change until the end of HD, regardless of the applied ultrafiltration-rate. This suggests that the fluid contribution from the legs is not only affected by the applied ultrafiltration but also by other physiological mechanisms. The latter slow changes in leg resistivity may continue up to 48 h after dialysis, as demonstrated in [24].

Relative changes in parameters extracted from kkBIS correlated well with intradialytic weight loss for stable patients. This correlation was weaker for unstable patients, likely due to medical interventions for IDH. In particular, interventions involving switching patients to the Trendelenburg position, administering parenteral fluid, or decreasing the ultrafiltration rate would generate a new fluid distribution across the body and impair the ability of BIS to correctly estimate fluid volumes [15, 25]. Pre- to post-dialysis, the mean difference in change between $\Delta R_{e,whBIS}$ and $\Delta R_{e,kkBIS}$, normalized to weight loss, was significantly lower in stable patients compared to unstable ones ($p < 0.001$), Fig. 4. This further indicates that a smaller contribution from lower extremities is expected for IDH-prone patients.

In Fig. 5, we investigated the relationship between the accumulative reduction in ECF and the collected volume of the ultrafiltrate during the period of HD. For stable patients, whole-body ECF_{whBIS} is clearly reduced by UFV in a very linear 1:1 relationship throughout the HD treatment. For unstable patients, ECF_{whBIS} was further depleted by an amount of ~469.4 mL above UFV. This could be explained as some of the ECF may be shifted toward the intracellular compartment driven by osmotic gradient built up during HD. Another possible explanation is due to a BIS measurements error occurred when a great amount of fluid is removed from the trunk during HD. The thigh's ECF_{kkBIS} is depleted as well by UFV; however, with a significantly higher slope for unstable patients (slope: -0.17 ± 0.05) than for stable ones (slope: -0.11 ± 0.01). If the ratio of thigh's ECF_{kkBIS} to whole-body ECF_{whBIS} was to be considered, unstable patients are obviously characterised by significantly lesser values compared to stable one especially within the first half of the treatment. This particular parameter could potentially be used in the future to identify patients at risk of IDH early during the HD treatment.

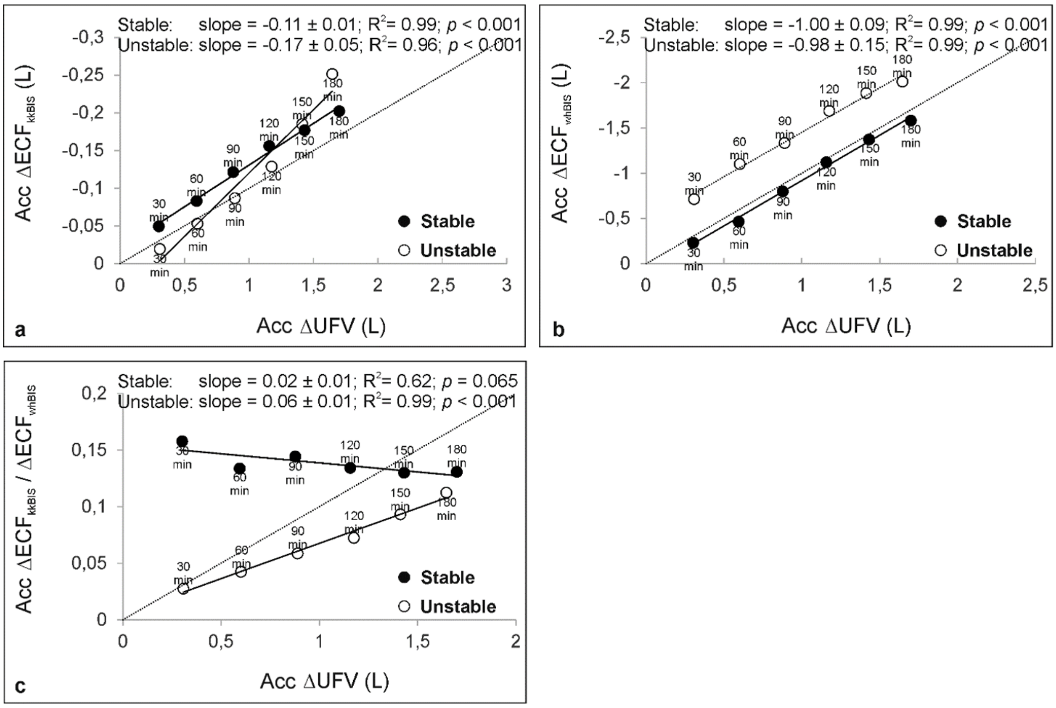

Fig.5: Data (mean ± SD) showing the accumulative changes in extracellular fluid (ECF) associated with accumulative ultrafiltration volume (UFV) as recorded by the dialysis machine during treatment at the time points 30, 60, 90, 120,150 and 180 min from the start of dialysis. SD lines were omitted from the graph to maintain visual clarity.

A limitation of this study is the small number of recruited patients. Nevertheless, having an equal number of patients in each group prevented a strong bias toward any group. In addition, findings were relatively consistent among patients within groups, suggesting that increased group sizes are unlikely to lead to different conclusions. Other errors are inherent to the BIS method itself, hence may affect the accuracy of kkBIS method as well.

The difference in cross-sectional area between different body segments, the regional fluid accumulation in certain body segments, and the alterations of body fluid distribution due to HD are all known to reduce the accuracy of BIS [19, 27, 28]. Nevertheless, the question of the accuracy of both methods, especially for ECF estimation, could not be adequately addressed in this study due to the lack of comparison against gold standards. Hence, this remains a field for further research.

In summary, due to some measurement limitations imposed by the standard electrode configurations of whole-body BIS method, alternative electrode configurations (e.g. dividing the body into segments in series) were suggested. These new configurations may further impairs patient comfort and increases the complexity of the method. Here we demonstrate that a BIS method measuring from knee to knee can monitor changes in body fluid volumes with a comparable accuracy as standard whBIS even in hemodynamically unstable patients. Knee to knee BIS thus be a simplified and more comfortable alternative to whole body BIS.

Acknowledgment

This work has been supported by the RWTH Exploratory Research Space (ERS) under the grant MTBo05.

Conflict of interest

Authors state no conflict of interest.

References

1. Zhu F, Rosales L, Kotanko P. Techniques for assessing fluids status in patients with kidney disease. Curr. Opin. Nephrol. Hypertension 2016;25: 473-9. https://doi.org/10.1097/mnh.0000000000000273
2. Shoji T, Tsubakihara Y, Fujii M, Imai E. Hemodialysis-associated hypotension as an independent risk factor for two-years mortality in hemodialysis patients. Kidney Int. 2004;66: 1212-20. https://doi.org/10.1111/j.1523-1755.2004.00812.x
3. Kuhlmann MK, Zhu F, Seibert E, Levin NW. Bioimpedance, dry weight and blood pressure control: new methods and consequences. Curr. Opin. Nephrol. Hypertension 2005;14: 543–549. https://doi.org/10.1097/01.mnh.0000185983.48319.00
4. Krämer M, Rode C, Wizemann V. Detection limit of methods to assess fluid status changes in dialysis patients. Kidney Int. 2006;69: 1609-20. https://doi.org/10.1038/sj.ki.5000286
5. Moissl UM, et al. Body fluid volume determination via body composition spectroscopy in health and disease. Physiol. Meas. 2006:27: 921-33.
6. Zhu F, Schneditz D, Wang E, Levin NW. Dynamics of segmental extracellular volumes during changes in body position by bioimpedance analysis. J. Appl. Physiol. (1985) 1998;85: 497-504. https://doi.org/10.1152/jappl.1998.85.2.497
7. Zhu F, Schneditz D, Levin NW. Sum of segmental bioimpedance analysis during ultrafiltration and hemodialysis reduces sensitivity to changes in body position. Kidney Int. 1999;56: 692-699. https://doi.org/10.1046/j.1523-1755.1999.00588.x
8. Heitman BL. Impedance: a valid method in assessment of body composition?. Eur. J. Clin. Nutr. 1994;48: 228-40.
9. Medrano G, Eitner F, Floege J, Leonhardt S. A novel bioimpedance technique to monitor fluid volume state during hemodialysis treatment. ASAIO J. 2010;56: 215-20. https://doi.org/10.1097/mat.0b013e3181d89160
10. Cole K, Cole R. Dispersion and absorption in dielectrics. I. alternating-current characteristics. J. Chem. Phys. 1941;9: 341-51.
11. De Lorenzo A, Andreoli A, Matthie J, Withers P. Predicting body cell mass with bioimpedance by using theoretical methods: a technological review J. Appl. Physiol. 1997;82: 1542-58. https://doi.org/10.1152/jappl.1997.82.5.1542
12. Fenech M, Jaffrin M Y. Extracellular and intracellular volume variations during postural change measured by segmental and wrist-ankle bioimpedance spectroscopy. IEEE Trans. Biomed. Eng. 2004;51: 166-75. https://doi.org/10.1109/tbme.2003.820338
13. Matthie J R. Second generation mixture theory equation for estimating intracellular water using bioimpedance spectroscopy. J. Appl. Physiol. 2005;99: 780-81. https://doi.org/10.1152/japplphysiol.00145.2005
14. Medrano G, Eitner F, Walter M, Leonhardt S. Model-based correction of the influence of body position on continuous segmental and hand-to-foot bioimpedance measurements. Med. Biol. Eng. Comput. 2010;48: 531-41. https://doi.org/10.1007/s11517-010-0602-5
15. Abbas SR, Zhu F, Kaysen GA, Kotanko P, Levin NW. Effect of change in fluid distribution in segments in hemodialysis patients at different ultrafiltration rates on accuracy of whole body bioimpedance measurement. J Appl. Physiol. 2014;116: 1382-9. https://doi.org/10.1152/japplphysiol.01361.2013
16. Zhu F et al. Segment-specific resistivity improves body fluid volume estimates from bioimpedance spectroscopy in hemodialysis patients. J. Appl. Physiol. 2006;100: 717–724. https://doi.org/10.1152/japplphysiol.00669.2005
17. Ismail AH et al. Usefulness of bioimpedance spectroscopy for detection of hypotensive episode during dialysis. ASAIO J. 2014;60: 570-5.
18. Cox-Reijven P L, Van Kreel B, Soeters PB. Bio-electrical impedance spectroscopy: alternatives for the conventional hand-to-foot measurements. Clin. Nutr. 2002;21: 127-33. https://doi.org/10.1054/clnu.2001.0521
19. Scharfetter H, Wirnsberger GH, Holzer H, Hutten H. Influence of ionic shifts during dialysis on volume estimations with multifrequency impedance analysis. Med. Biol. Eng. Comput. 1997;35: 96-102. https://doi.org/10.1007/bf02534137

20. Shulman T, Heidenheim AP, Kianfar C, Shulman SM, Lindsay RM. Preserving central blood volume: changes in body fluid compartments during hemodialysis. ASAIO J. 2001;47: 615-8. https://doi.org/10.1097/00002480-200111000-00009
21. Zhu F et al. Adjustment of dry weight in hemodialysis patients using intradialytic continuous multifrequency bioimpedance of the calf. Int. J. Artif. Organs. 2004;27: 104-9. https://doi.org/10.1177/039139880402700205
22. Zhu F, Schneditz D, Wang E, Martin K, Morris AT, Levin NW. Segmental bioimpedance measurements during hemodialysis. ASAIO J. 1998;44: M541-5. https://doi.org/10.1097/00002480-199809000-00045
23. Zhu F, Leonard EF, Levin NW. Extracellular fluid redistribution during hemodialysis: bioimpedance measurement and model. Physiol. Meas. 2008;29: S491-501. https://doi.org/10.1088/0967-3334/29/6/s41
24. Jain AK, Lindsay RM. Intra and extra cellular fluid shifts during the inter dialytic period in conventional and daily hemodialysis patients. ASAIO J. 2008;54: 100-3. https://doi.org/10.1097/mat.0b013e318162c404
25. Carter M, Morris AT, Zhu F, Zaluska W, Levin NW. Effect of body mass index (bmi) on estimation of extracellular volume (ecv) in hemodialysis (hd) patients using segmental and whole body bioimpedance analysis. Physiol. Meas. 2005;26: S93–99. https://doi.org/10.1088/0967-3334/26/2/009
26. Scharfetter H, Monif M, László Z, Lambauer T, Hutten H, Hinghofer-Szalkay H. Effect of postural changes on the reliability of volume estimations from bioimpedance spectroscopy data. Kidney Int. 1997;51: 1078-87. https://doi.org/10.1038/ki.1997.150
27. Baumgartner RN, Chumlea WC, Roche AT. Estimation of body composition from segmental impedance. Am. J. Clin. Nutr. 1989;50: 221-5.
28. Fuller NJ, Elia M. Potential use of the bioelectrical impedance of the ‘‘whole body’’ and of body segments for the assessment of body composition: comparison with densitometry and anthropometry. Eur. J. Clin. Nutr. 1989;43: 779-91.