Can tissue dielectric constant measurements assess circulating blood volume changes in patients undergoing haemodialysis?

Ken-Taro Toyooka¹, Hidetomo Niwa¹,², Eiji Hashiba² and Kazuyoshi Hirota³

¹Department of Anesthesiology, Hirosaki University Hospital, Hirosaki, Japan, ²Division of Intensive Care Unit, Hirosaki University Hospital, Hirosaki, Japan and ³Department of Anesthesiology, Hirosaki University Graduate School of Medicine, Hirosaki, Japan

Summary

Background The tissue dielectric constant (TDC) method uses an open-ended coaxial probe to achieve non-invasive measurement of water content in skin. The aim of our study was to test the hypothesis that the changes in circulating blood volume would be associated with the changes in TDC values in patients undergoing haemodialysis.

Methods In this prospective descriptive study, TDC measurements were performed for three parts of the body (the face, shin and hand) before and after patients underwent haemodialysis (N = 83). The primary outcome measure was the correlation between the amount of water removal and ΔTDC at each body site measured (ΔTDC = posthaemodialysis TDC–prehaemodialysis TDC). The secondary outcome measure was the mean difference in TDC value before and after haemodialysis.

Results The TDC values measured at each part of the body were significantly reduced after haemodialysis, but the percentage difference between pre- and posthaemodialysis was small for the face, shin and hand, with %mean ± SE values of −4.4 ± 0.70, −3.2 ± 0.98 and −6.0 ± 1.6; 95 per cent confidence intervals (lower bound to upper bound) of 3.0–5.8, 1.3–5.2 and 2.7–9.2; and P values of P = 0.000, P = 0.000 and P = 0.000, respectively. The inverse correlation between ΔTDC and the amount of water removal was also weak (correlation at the face, r = −0.25, P = 0.028; at the shin, r = −0.26, P = 0.018; and at the hand, no significant correlation).

Conclusion Our results indicate that TDC measurement can be used to assess the changes in local oedema, but may be unlikely to evaluate real-time changes in the circulating blood volume in a clinical setting.

Introduction

The tissue dielectric constant (TDC) method is capable of taking non-invasive measurement of water content in the skin and/or subcutaneous fat using an open-ended coaxial probe with a high-frequency electromagnetic wave of 300 MHz (Nuutinen et al., 2004). This method has been applied for evaluating the grade of local tissue oedema (primarily in the limbs) in a variety of clinical settings (Mayrovitz et al., 2008, 2009a, b; Mayrovitz et al., 2013, 2014; Birkballe et al., 2014; Lahtinen et al., 2015). Oedema of the lower limbs in patients with diabetes mellitus has been associated with an increased TDC value (Mayrovitz et al., 2013). In another study, manual lymphatic drainage therapy reduced the lymphoedema of the upper limbs in post-mastectomy patients, and this change was reflected in a decreased TDC for the upper limbs (Mayrovitz et al., 2008).

Local oedema is in part associated with an increased blood volume due to heart and/or renal failure. Decreased circulating blood volume from the use of diuretics can reduce local oedema in such patients. From this viewpoint, we hypothesized that the changes in circulating blood volume of patients would be associated with the changes in the TDC value of local tissue. In this study, we considered that maintenance haemodialysis patients were appropriate subjects for testing our hypothesis because haemodialysis causes a clear decrease in a patient’s circulating blood volume. To test our hypothesis, we thus determined the TDC measurements in patients who underwent scheduled haemodialysis, and evaluated the relationship between changes in TDC values and those in the circulating blood volume.
Materials and methods

Study design and patients

Before the study was begun, we obtained the approval of our university’s Medical Ethics Committee (Hirosaki University Graduate School of Medicine, Hirosaki, Japan; approval no. 2013-118) as well as written informed consent from the 83 patients. The trial was registered with the University Hospital Medical Information Network (registration no. UMIN000017418). This prospective descriptive study was carried out at Hirosaki University Hospital, Hirosaki, Japan. Consecutive patients who underwent haemodialysis between May 2015 and February 2016 were assessed for eligibility. The candidates for inclusion in the study were maintenance dialysis patients aged ≥18 years.

TDC measurement

Each patient’s TDCs were measured using a desktop MoistureMeter-D (Delfin Technologies, Kuopio, Finland) by a single anaesthesiologist (K.T.). The desktop MoistureMeter-D consists of a measuring unit and four probes for different measurement depths from 0.5—5 mm. The M25 probe with 2.5 mm measurement depth was used in this study. This depth is considered effective for evaluating the grade of local oedema (Mayrovitz et al., 2009a,b).

Tissue dielectric constants of the face, hand and shin of each patient were taken before and after the patient underwent haemodialysis. Baseline TDCs were measured when the patient first assumed a supine position, before the start of haemodialysis. During the dialysis, the patients were allowed to change positions on the bed at will. The hand measurements were made on the dorsal skin between the thumb and forefinger of one hand without an arteriovenous shunt. The shin measurement was made on the same side of the middle tibia as the hand measurements. Face measurements were made on the same side as the hand measurement, just below the eye. All three standardized measurement sites were marked with a dot-shaped seal. The measurements were conducted by placing the probe above the dot-shaped seal in contact with the skin using gentle pressure. Three replications were made at each measurement site. The mean of two or three consecutive readings with a coefficient of variation below 15% at one site of interest was used.

Haemodialysis procedure

Body weight measurement was performed in all patients upon their arrival at the haemodialysis room. The scheduled amount of water removal for each patient was thus determined based on the increase in body weight over the dry weight. The duration of the procedure was determined by nephrologists or urologists in consideration of the patient’s dialysis tolerance. Haemodialysis was performed using a standardized haemodialysis machine in our hospital (TR7700M; Toray Medical, Tokyo, Japan). We were able to determine the amount of water removed from patients at any time point by checking the water-removal ‘metre’ on the screen of the dialysis machine. After patients underwent haemodialysis, their body weights were measured again.

The primary outcome measure

The primary outcome measure was the correlation between the amount of water removal and ΔTDC at each body site measured. ΔTDC was defined as the difference in the TDC values between before and after haemodialysis (ΔTDC = TDC after haemodialysis – TDC before haemodialysis).

Secondary outcome measure and other collected data

The secondary outcome measure was the mean difference in the TDC of each measured site between before and after haemodialysis. The following demographical and haemodialysis data were collected: age, body mass index, reasons for haemodialysis, amount of water removal, duration of haemodialysis and patients’ weight loss due to water removal. We also evaluated the correlation between the amount of water removal and the patients’ weight loss.

Statistical analysis

For tests of association using Pearson correlations, a moderate correlation between variables was considered meaningful. To detect a moderate correlation (r = 0.3), a sample of 82 analyzable subjects will provide 80% power to discover that the correlation is statistically different from no correlation at the 0.05 significance level. For continuous variables with a normal distribution, the mean [± standard deviation (SD) or standard error (SE)] is reported. For variables not normally distributed, the median and interquartile ranges are reported. P-values <0.05 were considered significant. Student’s t-test was used for continuous variables with normal distributions. The Mann–Whitney rank-sum test was used for continuous variables without a normal distribution. Correlations between the amount of water removal and ΔTDC at each body site (the primary outcome) or the patients’ weight loss were analysed using Pearson’s product-moment correlation coefficient. Sample size calculations were performed using G*Power 3 software (Heinrich-Heine-University Institute of Experimental Psychology, Düsseldorf, Germany; Faul et al., 2007, 2009). All statistical analyses were conducted with IBM SPSS® statistics ver. 22.0 software (IBM, Tokyo, Japan).

Results

A total of 83 patients treated in the period from September 2015 to March 2016 were included in the analyses. The demographics of the patients and haemodialysis data are
summarized in Table 1. Patients’ weight loss after haemodialysis was compatible with the amount of water removal determined using a dialysis machine. A strong inverse correlation was also observed between the amount of water removed and the patients’ weight loss ($r = 0.91$, $P = 0.000$).

### Primary outcome measure

As shown in Fig. 1, there was an inverse correlation between the amount of water removed and the ΔTDC at the face or shin in patients with haemodialysis (at the face, $r = 0.25$, $P = 0.028$; at the shin, $r = 0.26$, $P = 0.018$). In contrast, the ΔTDC of the hand showed no correlation with the amount of water removed.

### Secondary outcome measure

The secondary outcome measure was the mean difference in the TDC of each measured site between before and after haemodialysis. The TDC value measured before haemodialysis was defined as the baseline. The TDC values measured at all body sites were significantly decreased after patients underwent haemodialysis compared with the baseline (Table 2).

### Discussion

Our starting hypothesis was that the changes in the circulating blood volume of patients would be associated with the changes in the TDC value of local tissue. In the present study, we found that the TDC values measured at local tissues were significantly decreased after patients underwent haemodialysis. However, the percentage difference in the TDC values between the baseline and after haemodialysis was small ($-3.2\%$ to $-6.0\%$). In a similar fashion, a correlation between ΔTDC and the amount of water removal was also weak ($r = -0.25$ or $-0.26$). The finding of a correlation of 0.25 suggests that only 6% of the variation was attributable to

---

**Table 1** Characteristics of the patients and their dialysis data (n = 83).

| Characteristic                          | Mean ± SD or Median [IQR] |
|----------------------------------------|---------------------------|
| Age (years)                            | 64.4 ± 12.2               |
| Male/Female (n)                        | 60/23                     |
| Height (cm)                            | 160.6 ± 10.4              |
| Body weight (kg)                       | 58.9 [14.8]               |
| Removed water (ml)                     | 1800 [960]                |
| Weight loss (kg)                       | -1.8 [-1.18]              |
| Duration of haemodialysis (h)          | 4.0 [1.0]                 |
| Removed water velocity (ml/h)          | 490 [280]                 |
| Causes of haemodialysis n (%)          |                           |
| Kidney/Bladder/Ureter tumour           | 4 (4.8)                   |
| Chronic glomerulonephritis             | 12 (14.5)                 |
| Diabetic nephropathy                   | 29 (34.9)                 |
| Polycystic kidney                      | 4 (4.8)                   |
| Nephrosclerosis                        | 4 (4.8)                   |
| Myeloma kidney                         | 1 (1.2)                   |
| Rapidly progressive glomerulonephritis | 4 (4.8)                   |
| Nephrotic syndrome                     | 1 (1.2)                   |
| Chronic heart failure                  | 15 (18.0)                 |
| Rheumatoid arthritis                   | 1 (1.2)                   |
| Unknown                                | 8 (9.6)                   |

Data are expressed as the means ± SDs or medians [interquartile ranges].

© 2017 The Authors. Clinical Physiology and Functional Imaging published by John Wiley & Sons Ltd on behalf of Scandinavian Society of Clinical Physiology and Nuclear Medicine 38, 3, 497–501
Table 2  The absolute TDC values at three anatomical sites before/after HD.

|        | Face | Shin | Hand |
|--------|------|------|------|
| TDC before HD | 39.0 ± 0.76 | 41.0 ± 1.18 | 39.3 ± 0.95 |
| TDC after HD  | 37.3 ± 0.77 | 39.5 ± 1.16 | 36.6 ± 0.88 |
| (%TDC after/ before HD) | (95.6 ± 0.70) | (96.8 ± 0.98) | (94.0 ± 1.64) |
| Mean difference | −1.7 ± 0.28 | −1.4 ± 0.39 | −2.7 ± 0.54 |
| (%difference)   | (−4.4 ± 0.70) | (−3.2 ± 0.98) | (−6.0 ± 1.64) |
| P value        | 0.000 | 0.000 | 0.000 |

Data are expressed as the means ± SEM; TDC, tissue dielectric constant; HD, haemodialysis; %TDC after/before HD = TDC value after HD/TDC value before HD*100.

water changes. Our results thus indicate that TDC measurement is unlikely to be a reliable index of changes in the circulating blood volume of patients.

A possible explanation for this inconsistency with our hypothesis would be as follows. In theory, the decreased circulating blood in the vessels due to the haemodialysis draws excessive water from the interstitial tissues into the capillary vessels to be equilibrated. Such water shift normalizes the circulating blood volume and reduces the local oedema. This would require more time than the length of the present study period. From this point of view, if we had conducted the TDC measurement later, a higher correlation and a bigger difference in the TDC value would likely have been obtained in our study. Based on this theory, the results of our study can be interpreted as that the TDC measurement detects the decreased local water content in an early phase of 'fluid equilibrium' after haemodialysis. Our results thus indicate that TDC measurement can only be used as an index of changes in local water volume and detect even slight changes in the local oedema, but would be less likely to accurately represent the circulating blood volume in real time.

One prospective descriptive study showed that there was a moderate positive correlation between the increase in the TDC value and weight gained during the postoperative period in patients undergoing cardiac surgery (r = 0.60, P<0.01, n = 29) (Petaja et al., 2003). In accordance with the theory described above, Petaja’s result can be taken to mean that positive fluid balance after surgery increased local tissue water (i.e. oedema) as well as the body weight of patients. Another clinical study showed that there was a highly significant correlation between the decreasing TDC value and removed water in patients who underwent haemodialysis (r = −0.99, P<0.01, n = 7) (Nuutinen et al., 2004). Probably they would have enough time of tissue water to be equilibrated.

A possible limitation of our study is that it was a descriptive study conducted in a limited number of patients. In the future, the efficacy of the TDC method will need to be tested in a variety of patients.

We concluded that TDC measurement is unlikely to be a reliable index of real-time changes in the circulating blood volume, but can be sensitive to assess changes in local water content. Our results confirmed the current understanding that TDC measurement can be used to assess changes in the water content of local tissues. However, further studies will be needed to confirm that TDC measurement is unreliable for the real-time measurement of circulating blood volume.

Conflict of interest

The authors have no conflict of interests to declare.

Author's contributions

K.T. measured the tissue dielectric constant and wrote the first draft of the manuscript; H.N. designed the study, analysed the data and wrote the first draft of the manuscript; K.H. supervised the study; E.H. supervised the measurement of the tissue dielectric constant.

References

Birkballe S, Jensen MR, Noerregaard S, et al. Can tissue dielectric constant measurement aid in differentiating lymphoedema from lipoedema in women with swollen legs? Br J Dermatol (2014); 170: 96–102.

Faul F, Erdfelder E, Lang AG, et al. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behav Res Methods (2007); 39: 175–191.

Faul F, Erdfelder E, Buchner A, et al. Statistical power analyses using G*Power 3.1: tests for correlation and regression analyses. Behav Res Methods (2009); 41: 1149–1160.

Laitinen T, Seppala J, Viren T, et al. Experimental and Analytical Comparisons of Tissue Dielectric Constant (TDC) and Bioimpedance Spectroscopy (BIS) in Assessment of Early Arm Lymphedema in Breast Cancer Patients after Axillary Surgery and Radiotherapy. Lymphot Res Biol (2015); 13: 176–185.

Mayrovitz HN, Davey S, Shapiro E. Localized tissue water changes accompanying one manual lymphatic drainage (MLD) therapy session assessed by changes in tissue dielectric constant inpatients with lower extremity lymphedema. Lymphology (2008); 41: 87–92.

Mayrovitz HN, Davey S, Shapiro E. Suitability of single tissue dielectric constant measurements to assess local tissue water in normal and lymphedematous skin. Clin Physiol Funct Imaging (2009a); 29: 123–127.

Mayrovitz HN, Weingrad DN, Davey S. Local tissue water in at-risk and contralateral forearms of women with and without breast cancer treatment-related lymphedema. Lymphot Res Biol (2009b); 7: 153–158.

Mayrovitz HN, McClaymont A, Pandya N. Skin tissue water assessed via tissue dielectric constant measurements in persons with and without diabetes mellitus. Diabetes Technol Ther (2013); 15: 60–65.

Mayrovitz HN, Weingrad DN, Davey S. Tissue dielectric constant (TDC) measurements as a means of characterizing
localized tissue water in arms of women with and without breast cancer treatment related lymphedema. Lymphology (2014); 47: 142–150.

Nuutinen J, Ikaheimo R, Lahtinen T. Validation of a new dielectric device to assess changes of tissue water in skin and subcutaneous fat. Physiol Meas (2004); 25: 447–454.

Petaja L, Nuutinen J, Uusaro A, et al. Dielectric constant of skin and subcutaneous fat to assess fluid changes after cardiac surgery. Physiol Meas (2003); 24: 383–390.