

# Ratio of Capacitance/BMI Reflects Deficit in Nutritional Concentration While $CH^2$ Reflects Total Nutritional Deficit in CAPD Patients and General Population<sup>\*#</sup>

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## ABSTRACT

Traditionally phase angle was the best predictor in BIA for nutrition and survival in dialysis population. We recently showed that normalized bioimpedance indices are a better risk discriminator for dialysis patients and the general population. We hereby aimed to explore discriminating factors behind them. **Methods:** We assessed the body capacitive index ( $BCI = \text{Capacitance} \times \text{Height}^2 / \text{Weight}$ ); body resistive index ( $BRI = \text{Resistance} \times \text{Weight} / \text{Height}^2$ ); and also,  $CH^2$  ( $= \text{Capacitance} \times \text{Height}^2$ ) which represents total body capacitive volume in physics. We initially performed BIA for 206 female, 116 male healthy volunteers, followed by, prospective study for 128 CAPD patients (47 diabetes mellitus (DM), 81 non-DM; 59 male, 69 female) for >2 years. **Results:** Moderately good negative correlation of albumin and BCI ( $r = -0.533$ ,  $p < 0.001$ ) with linear regression ( $BCI = 8.780 - 0.184 \times [\text{albumin}]$ ,  $R^2 = 0.339$ ,  $p < 0.001$ ) was shown in CAPD patients. BCI and  $CH^2$  were much higher in CAPD patients in comparison to healthy volunteers ( $3.4 \pm 0.1$  vs  $2.0 \pm 0.0$  nFm<sup>2</sup>/kg,  $p < 0.001$  and  $203 \pm 8$  vs  $125 \pm 1$  nFm<sup>2</sup>,  $p < 0.001$ , respectively). In age and gender adjusted logistic regression model of 128 CAPD patients versus 322 healthy volunteers, the best risk discriminator was BCI ( $X^2 = 165.6$ ), followed by  $CH^2$  ( $X^2 = 140$ ), phase angle ( $X^2 = 59.3$ ) and BRI ( $X^2 = 52.2$ ). Thirty five (27.3%) patients died during the study period (Fatal cause: infection (54%), cardiovascular (26%)). In Cox regression,  $CH^2$  ( $X^2_4 = 32.4$ ) was the best predictor for all-cause mortality, followed by BCI ( $X^2_4 = 27.7$ ) and phase angle ( $X^2_4 = 19.3$ ). **Conclusion:** The phase angle was a compound parameter of the body capacity index (BCI) and body resistive index (BRI). BCI has a moderately good negative correlation with albumin and this supports its role in reflecting the severity of malnutrition in CAPD patients.  $CH^2$  represents total nutrition deficit and thus the major risk indicator for the survival of CAPD patients.

**Keywords:** Bioimpedance Analysis; Continuous Ambulatory Peritoneal Dialysis; Comparison with General Population; Nutrition; Survival

## 1. Introduction

Bioimpedance analysis (BIA) has been recognized as a powerful tool to assess nutrition and hydration status in patients on CAPD [1-4] with standardized methodology [5,6] and various resistive indexes have been described [7-9]. We have recently shown that normalized capaci

tive indices (e.g., Capacitance/Body Mass Index and Capacity  $\times$  Height<sup>2</sup>) carried more predictive value than non-normalized parameter like the phase angle [10]. Here we aim to further explore the physics rationale of such parameters by analyzing our cohort of CAPD patients and the general population.

Gender differences in non normalized bioimpedance parameters (e.g., phase angle and resistive index) have been reported [11,12]. However we have demonstrated that these gender differences disappeared when normal-

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ized bioimpedance parameters (e.g., body capacitive index) were used [10]. The higher body resistive index (BRI) in female normal subjects is probably due to the higher percentage of fat which resulted in the lower phase angle [10].

This current study serves to further verify the roles of varying normalized bioimpedance parameters with various analytical models in line with current thought of translating physiological science into clinical practice [13], as well as exploring the underlying risk discriminating factor.

## 2. Methods

### 2.1. Study Design and Population

We initially surveyed the bioimpedance profile of the general population by recruiting 322 healthy volunteers as representation of normal population in the neighbourhood of our hospital. We then prospectively studied all stable CAPD patients (a total of 128 patients) in Kuala Lumpur Hospital. These patients were performing 4 exchanges a day with 3 exchanges during daytime and a long dwell at night. The study subjects were followed up for 2.2 to 2.3 years.

### 2.2. Bioelectric Impedance Analysis (BIA)

BIA was performed at time of enrolment, with Bioelectrical Impedance Analyzer, Maltron Bioscan 916 v3, with single frequency 50 kHz with alternating sinusoidal current, 0.7 mA on all CAPD patients with emptied peritoneal cavity in tetrapolar placement on the hand and foot. After the patient drained off the dialysate and was in a supine position for at least 10 minutes, the standard tetrapolar electrodes were placed on the dorsum of the wrist and anterior aspect of the ankle on the left side of the body [1]. Bioimpedance measurements obtained at the time of enrollment were used in the predictive model for this study.

The clinical value of BIA indexes has been postulated in previous study [7,8]. We derived body resistive index (BRI), body capacitive index (BCI),  $CH^2$  or  $H^2/X_C$  with the formulae from **Appendix A**.

Fat free mass, fat mass and fat percentage were derived with equation of Fat Mass = Weight – Fat Free Mass and fat percentage = Fat Mass / Weight  $\times$  100%, in which calculation of fat free mass were as described in past literature by Kotler *et al.* [14].

### 2.3. Statistical Methods

The statistical data were analyzed using Microsoft excel and SPSS (Statistical package for Social Science. SPSS Inc. 233 South Wacker Drive, 11<sup>th</sup> Floor, Chicago, Illinois 60606-6307). Kolmogorov Smirnov test was initially used to determine whether the data is in statistical

normal distribution. Logarithm transformation would be performed to achieve statistical normal distribution in data with non-normal distribution. Parametric test would be performed in data with normal distribution. In parameter that could not achieve normal distribution even with logarithm transformation with low number of analyzed subjects, non-parametric test would be utilized.

Logistic regression was used to identify the best risk discriminator among BIA parameters between Malaysian normal population and CAPD cohort in **Table 1**.

All means were presented with  $\pm$  standard error of mean ( $\pm$  SEM). Demographic features, blood investigations, peritoneum equilibrium test, anthropometry and BIA parameters of CAPD patients were studied to identify the risk factors for mortality in **Table 2**. Univariate analysis was performed with parametric test (e.g., student t-test, ANOVA) for survival comparison in data with statistical normal distribution, whereas non-parametric test (e.g., Mann Whitney U test) would be used in others. Factors that significantly affect the predictor and survival were analyzed with ANCOVA test.

In study of correlation relationship between data, Spearman correlation was used as non-parametric test. Cox regression was performed to analyse the significance of the relevant clinical parameters in survival (**Table 3**).

This was a prospective observational study of clinical practice, applying BIA and other investigations in CAPD patients. The protocol was in consistence with the principles of the Declaration of Helsinki as amended in Tokyo (1975), Venice (1983), and Hong Kong (1989) [15].

## 3. Results

### 3.1. Healthy Volunteers

We enrolled 322 healthy volunteers, *i.e.*, 206 female and 116 male healthy volunteers. They consist of 178 Malays, 89 Chinese, 54 Indians and 2 of other ethnicity. Their age ranged from 16 to 68 years old with the median of 38 years.

### 3.2. BIA Parameters of CAPD Patients and Correlation with Serum Albumin

We subsequently enrolled 128 CAPD patients with ethnicity composed of 64 Malays, 50 Chinese and 14 Indians. Aetiology of renal failure included diabetes mellitus (43 patients); chronic glomerulonephritis (27 patients); hypertension (10 patients); obstructive uropathy (6 patients); adult polycystic kidney disease (1 patient); concurrent diabetes nephropathy and obstructive uropathy (4 patients); while 37 patients have unknown cause of renal failure.

For the CAPD patients, albumin level has the best correlation with BCI ( $r = -0.533$ ,  $p < 0.001$ ), followed by phase angle ( $r = 0.520$ ,  $p < 0.001$ ), capacitance ( $r = -0.457$ ,  $p < 0.001$ ),  $X_C/H$  ( $r = 0.426$ ,  $p < 0.001$ ) and  $CH^2$  ( $-0.386$ ,  $r < 0.001$ ).

**Table 1. Logistic Regression Models with various BIA parameters adjusted for age and gender for CAPD patients versus Normal Population.**

Parameters	per Unit increment	Odds ratio	95% CI		p-value	$\chi^2$
			Lower bound	Upper bound		
<b><u>BIA parameter alone</u></b>						
Phase angle	per 1° increase	0.428	0.335	0.547	<0.001	59.3
Body Capacitive Index	per 1 nFm <sup>2</sup> /kg increase	19.028	9.168	39.490	<0.001	<b>165.6</b>
CH <sup>2</sup>	per 1 nFm <sup>2</sup> increase	1.047	1.035	1.059	<0.001	140.0
Body Resistive Index	per 1 Ωkg/cm <sup>2</sup> increase	0.010	0.003	0.041	<0.001	52.2
<b><u>Combined Model 1</u></b>						
Phase angle	per 1° increase	1.353	1.159	1.581	<0.001	8.2
Body Capacitive Index	per 1 nFm <sup>2</sup> /kg increase	34.854	14.320	84.833	<0.001	<b>114.6</b>
<b><u>Combined Model 2</u></b>						
Phase angle	per 1° increase	1.258	1.070	1.480	<0.001	4.0
CH <sup>2</sup>	per 1 nFm <sup>2</sup> increase	1.054	1.040	1.068	<0.001	84.8
<b><u>Combined Model 3</u></b>						
Phase angle	per 1° increase	0.505	0.400	0.637	<0.001	37.7
Body Resistive Index	per 1 Ωkg/cm <sup>2</sup> increase	0.021	0.005	0.089	<0.001	30.6
<b><u>Combined Model 4</u></b>						
Phase angle	per 1° increase	1.482	1.240	1.772	<0.001	13.9
Body Capacitive Index	per 1 nFm <sup>2</sup> /kg increase	15.585	6.046	40.171	<0.001	46.2
CH <sup>2</sup>	per 1 nFm <sup>2</sup> increase	1.030	1.015	1.045	<0.001	16.4
<b><u>Combined Model 5</u></b>						
Phase angle	per 1° increase	5	1	17	0.019	29.7
Body Capacitive Index	per 1 nFm <sup>2</sup> /kg increase	4280	127	144139	<0.001	115.8
Body Resistive Index	per 1 Ωkg/cm <sup>2</sup> increase	40770	228	7285483	<0.001	31.8

Abbreviation: CI, confidence interval.

Linear regression yielded:  $BCI = 8.780 - 0.184 \times [\text{albumin}]$ ,  $R^2 = 0.339$ ,  $p < 0.001$ .

### 3.3. Comparison of BIA Profile between Healthy Volunteers and CAPD Patients

Body capacity index and CH<sup>2</sup> were much higher in CAPD patients in comparison to healthy volunteers [ $3.4 \pm 0.1$  vs  $2.0 \pm 0.0$  nFm<sup>2</sup>/kg, ( $p < 0.001$ ) and  $203 \pm 8$  vs  $125 \pm 1$  nFm<sup>2</sup>, ( $p < 0.001$ ) respectively]. **Figures 1 and 2** demonstrated the difference in BCI and CH<sup>2</sup> between healthy volunteers and CAPD patients.

In logistic regression with 128 CAPD patients versus 322 healthy volunteers (**Table 1**), age and gender adjusted BIA parameter alone model showed that BCI has the highest risk discrimination, followed by CH<sup>2</sup>, phase angle and finally BRI. Phase angle have odds ratio per 1° increase of less than 1 because higher phase angle predict

better nutritional status. However when combined with body capacitive index (BCI) and CH<sup>2</sup> in combined model 1 and 2, the odds ratio of phase angle became more than 1. This is because the function of body resistive index is unmasked for phase angle, when a combined model built with body capacitive index. In contrast, combined model 5 showed that  $\chi^2$  value of phase angle was minimized and became insignificant when combined with body capacitive index and body resistive index because its functions in assessing capacitance and resistance of the body were replaced by BCI and BRI.

### 3.4. Survival Analysis

35 (27.3%) patients died during the study period. Infective (54%) and cardiovascular diseases (26%) were the main cause of death. The detail causes of death included: cardiac events, 6 patients; cerebral events, 3 patients;

**Table 2. Univariate analysis Comparison of clinical parameters during enrolment for survival.**

		Mean		p-value	p-value
		Survived	Died	Non-adjusted	Adjusted <sup>#</sup>
Age	year	48.7 ± 1.5	55.4 ± 2.3	0.018	0.141
Duration of dialysis	year	1.9 ± 1.1	2.2 ± 1.1	0.467	
BMI	kg/m <sup>2</sup>	24.3 ± 0.5	24.7 ± 0.7	0.716	
Albumin	g/L	30.1 ± 0.5	27.7 ± 0.9	0.016	0.028 <sup>##</sup>
TSF	cm	1.86 ± 0.10	1.82 ± 0.19	0.852	
MAC	cm	28.2 ± 0.5	29.1 ± 1.0	0.442	
MAMC	cm	22.4 ± 0.4	23.4 ± 0.6	0.190	
AMA	cm <sup>2</sup>	40.7 ± 1.3	44.1 ± 2.2	0.201	
Body Resistive Index	Ω kg/cm <sup>2</sup>	1.325 ± 0.032	1.294 ± 0.034	0.506	
Body Capacitive Index*	nFm <sup>2</sup> /kg	2.855	3.985	<0.001	0.004
CH <sup>2</sup> *	nFm <sup>2</sup>	168.70	244.73	<0.001	0.001
Phase angle**	°	4.86	3.58	<0.001	
Fat Percentage**	%	30.2	25.9	0.506	

Mean are expressed with ±standard error of mean. Student t-test was used for comparison except in data with \*\*. \*Geometric means were shown and compared. \*\*Medians were shown and Mann Whitney U test were performed. Anthropometry was measured using triceps skin fold thickness (TSF), mid arm circumference (MAC), mid arm muscle circumference (MAMC), and arm muscle area (AMA) and calculated using formulae of MAMC = MAC – π.TSF; and AMA = (MAC – π.TSF)<sup>2</sup> / 4π; #Univariate adjusted analysis with age, DM status and albumin via ANCOVA were performed for factor with normal distribution, if the unadjusted analysis by t-test demonstrated significant differences. ##Albumin analysis was adjusted with DM status and age.

**Table 3. Cox Regression Survival Hazard Ratio Model with various BIA parameters for CAPD patients.**

		95% CI				95% CI			
Parameters	per Unit increase	Hazard ratio	Lower bound	Upper bound	p-value	Hazard ratio	Lower bound	Upper bound	p-value
Model with phase angle						Model with Capacitive Index			
Age	per 1 year increase	1.022	0.996	1.050	0.097	1.030	1.002	1.059	0.036
Diabetes Status	DM:nonDM	1.402	0.680	2.891	0.359	1.597	0.769	3.315	0.209
Albumin	per 1 g/L increase	0.968	0.909	1.032	0.321	0.954	0.894	1.019	0.160
Phase angle	per 1° increase	0.454	0.310	0.664	<0.001				
Capacitive Index	per 1 nFm²/kg increase					1.389	1.139	1.695	0.001
Overall model*			$X^2_4 = 19.3$		0.001		$X^2_4 = 27.7$		<0.001
Model with X <sub>C</sub> /H						Model with CH²			
Age	per 1 year increase	1.024	0.997	1.053	0.087	1.028	1.000	1.058	0.053
Diabetes Status	DM:nonDM	1.187	0.561	2.511	0.654	1.275	0.592	2.743	0.535
Albumin	per 1 g/L increase	0.961	0.901	1.026	0.236	0.942	0.891	0.995	0.034
X <sub>C</sub> /H	per 1 Ω/cm increase	0.000	0.000	0.012	<0.001				
CH²	per 1 nFm² increase					1.006	1.003	1.009	<0.001
Overall model*			$X^2_4 = 17.5$		0.002		$X^2_4 = 32.4$		<0.001

Abbreviation: CI, confidence interval; \*Overall model tested were with Omnibus test of Model Coefficients. Note: CH<sup>2</sup> per 1 nFm<sup>2</sup> increase is replaceable by CH<sup>2</sup> per 100 nFm<sup>2</sup> increase with hazard ratio of 1.753 (CI: 1.302 - 2.368, p < 0.001), or H<sup>2</sup>/X<sub>C</sub> in the unit of cm<sup>2</sup>/Ω with hazard ratio of 1.002 (CI: 1.001 - 1.003, p < 0.001).

peritonitis, 7 patients; other infection, 12 patients; malignancy, 1 patient; other causes of death, 2 patients; unknown cause of death, 4 patients. Twenty out of 47 patients with diabetes died (43%) in comparison to 15 out of 81 non diabetic patients (19%) (p = 0.003). There was no gender predisposition for survival in this cohort with

52 out of 69 female patients (75%) survived and 41 out of 59 male patients (69%) survived (p = 0.458).

Adjusted univariate survival analyses were performed with age, diabetes mellitus status and albumin as in **Table 2**, for those parameters which had significant difference between the survival and fatal patients. We have

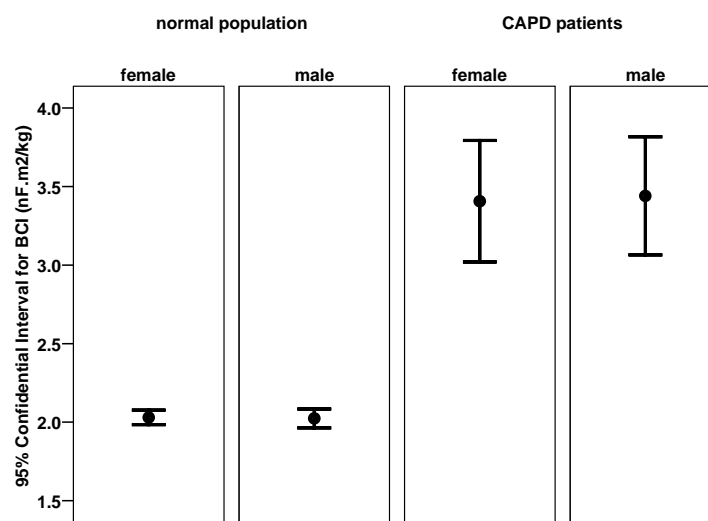


Figure 1. BCI of CAPD patients versus normal population.

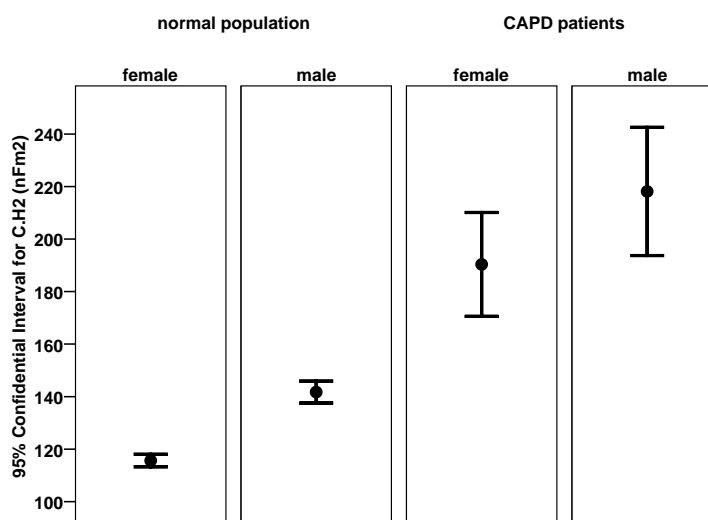


Figure 2. CH² of CAPD patients versus normal population.

previous reported the absent of correlation between survival and blood pressure, lipid profile, calcium, phosphate, ALP, iPTH, Hb, ESR, Kt/V, creatinine clearance, urea clearance and ultrafiltration in this cohort [8] and hence have limited the univariate analysis to salient factors, nutritional anthropometry assessment and bioimpedance. Surviving patients had significantly lower BCI (Figure 3), CH² (Figure 4) and phase angle.

We built 4 essential predictive models for survival prediction with Cox regression analysis. Table 3 showed that the overall survival of this cohort was best fitted into models with CH² (or H²/X<sub>C</sub>), with highest X² value followed by BCI, phase angle and X<sub>C</sub>/H.

#### 4. Discussion

In order to improve the evaluation of nutritional and hy-

dration status of the chronic dialysis patients, BIA has been advocated for both chronic ambulatory peritoneal dialysis (CAPD) patients [1,10,16,17] and hemodialysis patients [18-20]. Phase angle has been shown to be predictive of survival in dialysis population [21]. We have demonstrated that newer normalized bioimpedance parameters have better survival predictive value compared to phase angle [10]. However, the underlying factors influencing these normalized parameters and its physics rationale is still unsettling.

We evaluated these two parameters: body capacitive index (BCI), which is the product of capacitance and Height²/Weight, *i.e.*, ratio of capacitance over body mass index. In Appendix A, we demonstrated that it represents  $\epsilon/D$ , *i.e.*, the ratio of permittivity of dielectric in the body over density of body; and body resistive index (BRI), which is the product of resistance and Weight/Height².

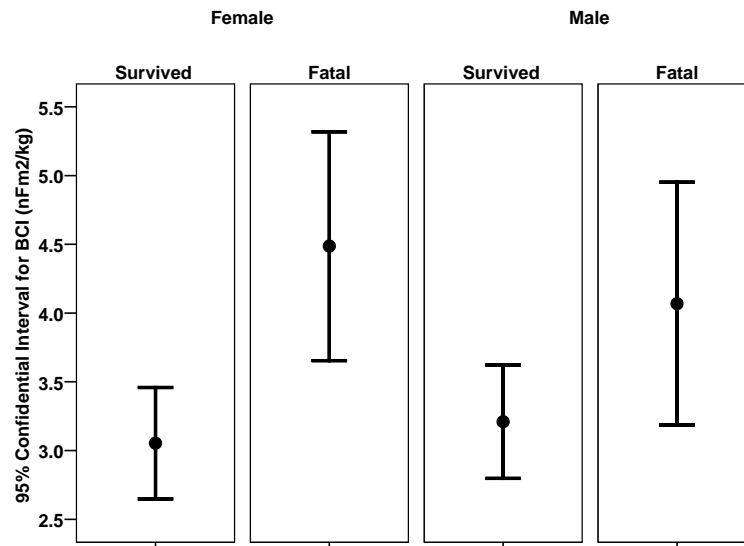


Figure 3. BCI at enrolment in Survived versus Fatal CAPD patients with 2 years follow-up.

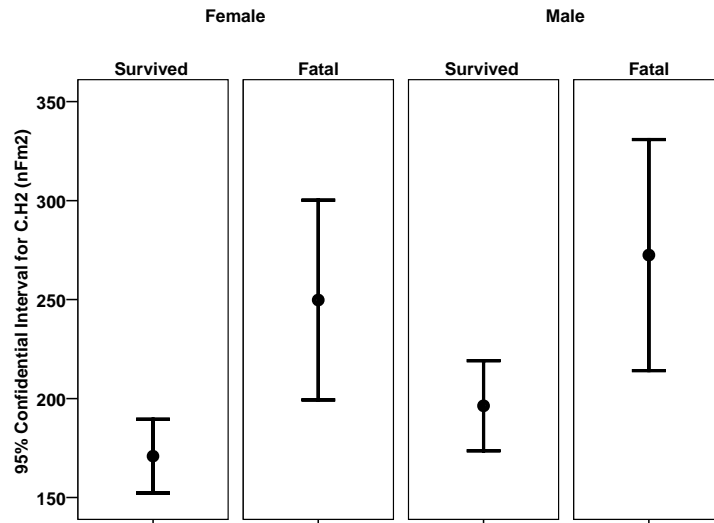


Figure 4. CH² at enrolment in Survived versus Fatal CAPD patients with 2 years follow-up.

The phase angle is actually the arctangent of  $1/\omega C_I R_I$ . We also showed that  $CH^2$  represents  $\varepsilon V$ , the total body capacitive volume in physics. BCI reflects nutritional deficit concentration, *i.e.*, both nutritional and hydration status while  $CH^2$  reflects total nutritional deficit. (Note that  $H^2/X_C = \omega CH^2$ — to compare the result with previous study of general population in Germany [7])

BCI correlated with albumin, better than all other parameters. Linear regression of BCI and albumin suggested that the presence of albumin and other unmeasured substance reduce the capacitive indexes. Previous literature has discussed regarding the survival predictive value of albumin [17] and the potential relation of hypoalbuminaemia with overhydration [16]. In current study, although BCI has higher predictive value than albumin alone in predictive model, we are still not able to differ-

entiate the causal-result relationship of fluid and nutrition with BCI.

Nonetheless, higher BCI in CAPD patients reflected their higher nutritional deficit concentration while higher  $CH^2$  reflected their higher total nutritional deficit. Logistic regression of various BIA parameters showed that body capacitive index is the main risk discriminator between CAPD patients and general population. This showed the marked change in the deficit in nutrition concentration with disease occurrence. The combined model of bioimpedance parameters revealed the interesting underlying interplay between BCI, BRI and phase angle. The hidden BRI property of phase angle unmasked and its risk discriminating property disappeared, when model involved phase angle and BCI. Meanwhile, the hidden BCI property of phase angle unmasked when it is in

combined model with BRI.  $CH^2$  is the second risk discriminator as total nutritional deficit would be increased when end stage renal failure set in.

Both  $CH^2$  and BCI were the key survival predictors for CAPD patients as demonstrated by Cox regression models (**Table 3**). Total nutrition deficit (with the marker of  $CH^2$ ) and nutritional deficit concentration (BCI) of a CAPD patient predicts his/her survival. Therefore, we proposed their assessment in line with noble clinical opinion of systematic nutritional assessment with bioimpedance for end stage renal failure patients [13,22-24].

Our previous study demonstrated that both BCI and  $CH^2$  were better risk indicators than phase angle because of the gender effect on the latter which actually makes it less discriminatory [10]. In addition, because BRI was non-significantly higher in survived than diseased patients, they reduced the phase angle of the survived patients mathematically and thus limited the survival predictability of the phase angle.

In short, we showed the better correlation of albumin and BCI in comparison to other bioimpedance parameters. And we also demonstrated the better risk discriminatory effect of BCI in comparison to phase angle with logistic regression which is not presented in our last paper [10].

Besides, we reported the use of single frequency BIA in determining the nutritional and hydration status of the patient as well as survival prediction [7,25-27]. We suggest further exploration in regard to resistive and capacitive indices [25,26] and extension of research into haemodialysis [28], HIV [29] and other diseases and healthy control populations. Certainly further study is needed to reaffirm the clinical role of BCI and  $CH^2$ . These are in line with current opinion on BIA research [22,30].

Unlike other sophisticated BIA derived parameters, BCI,  $CH^2$  and BRI are practical factors that easily measured and derived from height, weight, capacitance and resistance of the patient, in routine clinical assessment. Nevertheless, just like other BIA parameters, e.g., phase angle, the baseline normal reference of BCI and  $CH^2$  are needed for one to confidently conclude the extent of nutritional deficit. Gaining normal reference for various ethnic and disease population is one of the main hurdles in bioimpedance clinical use and we have shared this concern to the fellow researchers [31].

Recently, Zhu F *et al.* has significant break through with innovative advance using segment-specific resistivity to derive accurate water distribution information [32,33]. At the same time, phase angle of various body compartment was explored by Nescolarde L [34]. We hereby hope to propose that future research possibly should also look into segment-specific capacitive permissibility. One might be able to postulate higher significance in nutritional assessment and risk discriminating effect

with trunk capacitive index.

## 5. Conclusions

In summary, BCI represents nutritional deficit concentration with good negative correlation with albumin and was the main risk discriminator for CAPD patients versus general population. On the other hand,  $CH^2$  represents total nutrition deficit and thus the major risk indicator for the survival of CAPD patients. And, the traditionally measured phase angle was a compound parameter for BCI and BRI.

Further research for BCI, BRI and  $CH^2$  in other healthy community and other disease groups are needed before we could draw a firm conclusion to their specific role in physiology and clinical management.

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## Appendix A

For a given electrical conductor undergoing direct current, resistance is proportionately correlated with length and inversely proportionately correlated with area. It is generally hard to convert the cylinder model to human body. However, we could deduce their relationship with length (height) and weight with below approximation (7) with modification  $L = kH$ :

$$\begin{aligned} R &= \frac{\rho L}{A} = \frac{\rho L^2}{V} \\ \therefore D &= \frac{\text{Weight}}{V} \\ R &= \frac{\rho(kH)^2 \times D}{\text{Weight}} \\ \text{Let } BRI &= \rho k^2 D \\ BRI &= \frac{\text{Weight} \times R}{H^2} \text{ or } BRI = R \times BMI \end{aligned} \quad (1)$$

whereby  $R$  represents resistance;  $\rho$ , apparent resistivity of the conductor;  $A$ , Area;  $L$ , Length, converting to  $H$ , height in subsequent equations;  $D$ , density of the body;  $W$ , weight; BMI, body mass index;  $k$ , converting factor of body; And, Body resistive index ( $BRI$ ) reflects the product of resistivity of the body and density of body.

In same simulation model, during the alternative current, we assume that the cell membrane and other protein substance can act as a capacitor due to its dielectric property, where the  $A$  is area of cell membrane,  $L$  is the thickness of cell membrane plus body compartments, and  $\varepsilon$  is the permittivity of cell membrane. The reactance was calculated from wrist to ankle bioimpedance measurement which reflects all parallel connected cells in the body.

Therefore, the reactance of the capacitor is reflected by the below equations:

$$X_C = \frac{1}{\omega C} \quad (2)$$

whereby

$$\omega = 2\pi f$$

whereby  $C$ , capacitance;  $f$ , frequency of applied alternative current;  $X_C$ , reactance.

For a given capacitor consisting of 2 metal plates, the capacitance could be measured by:

$$C = \frac{\varepsilon A}{L}$$

whereby  $C$  represents capacitance;  $\varepsilon$ , permittivity of the dielectric between the two plates;  $A$ , Area;  $L$ , Distance between these plates.

Therefore, we could derive body capacitive index

( $BCI$ ), as well as  $C \cdot H^2$  for human in BIA with the below equation:

$$C = \frac{\varepsilon \times A}{L} = \frac{\varepsilon \times V}{k^2 H^2} = \frac{\varepsilon \times \text{Weight}}{k^2 D \times H^2} \quad (3)$$

$$\text{Let } BCI = \frac{\varepsilon}{k^2 D}$$

$$BCI = \frac{C \times H^2}{\text{Weight}} \text{ or } BCI = \frac{C}{BMI} \quad (4)$$

Besides, from Equation (3),

$$CH^2 = \frac{\varepsilon V}{k^2} \quad (5)$$

whereby  $V$  represents volume of body;  $D$ , density of body;  $H$ , height;  $k$ , converting factor of body.

Thus,  $BCI$  represents the ratio of capacitive permittivity over body density, while  $CH^2$  represents the total body capacitive volume in physics.

It is worth pointing out that the renowned terms of height<sup>2</sup>/reactance (5) could be derived with:

$$\frac{H^2}{X_C} = \omega C \times H^2 \quad (6)$$

Thus, the clinical implication of height<sup>2</sup>/reactance ( $H^2/X_C$ ) is equivalent to  $CH^2$ .

However, Height<sup>2</sup>/resistance is actually mathematically representing  $V/\rho$ :

$$\begin{aligned} R &= \frac{\rho k^2 H^2}{V} \\ \frac{H^2}{R} &= \frac{V}{\rho k^2} \end{aligned} \quad (7)$$

whereby  $R$  represents resistance;  $H$ , height;  $V$ , body volume;  $\rho$ , resistivity of body.

Phase angle ( $\alpha$ ) is defined mathematically as arc tangent of reactance over resistance, being measured in degree.

$$\alpha = \text{ArcTan} \frac{\text{Reactance}(X_C)}{\text{Resistance}(R)} = \text{ArcTan} \left( \frac{1}{\omega CR} \right) \quad (8)$$

From Equation (1),

$$R = \frac{BRI \times H^2}{\text{weight}} \quad (9)$$

From Equation (4),

$$C = \frac{\text{Weight} \times BCI}{H^2} \quad (10)$$

Putting the above Equations (9) and (10) into Equation (8), we get:

$$\frac{X_c}{R} = \frac{1}{\omega CR} = \frac{1}{\omega \times BCI \times BRI}$$

$$\alpha = \text{ArcTan}\left(\frac{1}{\omega BCI \times BRI}\right) \quad (11)$$

Take note that resistance for measurement of BRI in our current study is taken from direct current. Because of mathematically low phase angle range for all subjects and thus cosine is closed to 1, the body resistance in alternative current was thus not differed much from resistance in direct current.

Putting  $BCI = \frac{\varepsilon}{k^2 D}$  and  $BRI = \rho k^2 D$  into Equa-

tion (11)

$$\alpha = \text{ArcTan}\left(\frac{1}{\omega \frac{\varepsilon}{k^2 D} \times \rho k^2 D}\right) = \text{ArcTan}\left(\frac{1}{\omega \varepsilon \rho}\right) \quad (12)$$

Inserting these into Equation (8) with info from Equation (9) and (10), we get

$$CR = BCI \times BRI = \varepsilon \rho \quad (13)$$

Therefore,  $CR$ , the product of capacitance and resistance is representing  $\varepsilon \rho$ , *i.e.*, the product of resistivity of body and permittivity of body dielectric.