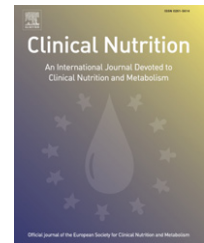




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ORIGINAL ARTICLE

New body fat prediction equations for severely obese patients

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KEYWORDS

Severe obesity;
Bioelectrical
impedance;
BOD POD;
Body composition;
Prediction equation

Summary

Background & aims: Severe obesity imposes physical limitations to body composition assessment. Our aim was to compare body fat (BF) estimations of severely obese patients obtained by bioelectrical impedance (BIA) and air displacement plethysmography (ADP) for development of new equations for BF prediction.

Methods: Severely obese subjects (83 female/36 male, mean age = 41.6 ± 11.6 years) had BF estimated by BIA and ADP. The agreement of the data was evaluated using Bland-Altman's graphic and concordance correlation coefficient (CCC). A multivariate regression analysis was performed to develop and validate new predictive equations.

Results: BF estimations from BIA (64.8 ± 15 kg) and ADP (65.6 ± 16.4 kg) did not differ ($p > 0.05$, with good accuracy, precision, and CCC), but the Bland-Altman graphic showed a wide limit of agreement (−10.4; 8.8). The standard BIA equation overestimated BF in women (−1.3 kg) and underestimated BF in men (5.6 kg; $p < 0.05$). Two BF new predictive equations were generated after BIA measurement, which predicted BF with higher accuracy, precision, CCC, and limits of agreement than the standard BIA equation.

Conclusions: Standard BIA equations were inadequate for estimating BF in severely obese patients. Equations developed especially for this population provide more accurate BF assessment.

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Introduction

Obesity is characterized by an excessive amount of **body fat (BF)** that accumulates mainly in abdominal region, and increases the risk for comorbidities such as hypertension, diabetes, and heart disease.^{1,2} Knowledge of the body composition of severely obese people could help to identify the risk of developing these comorbidities and play an important role in the planning and follow up of weight loss programs, mainly after bariatric surgery.³

The current methods used to evaluate the body composition in this population are limited by their inability to accommodate the large physical size of the subjects, or are inaccurate for use in extremely obese individuals. Dual-energy X-ray absorptiometry computerized tomography and nuclear magnetic resonance are limited by the size of the scanning area they can accommodate. Hydrostatic weighing is time-consuming and often disliked by patients. These methods are the reference methods used to evaluate BF, but are not available in many clinical settings and are impractical for use with most severely obese patients.^{3–5}

One of the most popular methods used to estimate BF in clinical practice is **bioelectrical impedance analysis (BIA)**. BIA is available in single (SF-BIA) and multifrequency (MF-BIA) models, and presents several advantages such as non-invasiveness, portability, and relatively low cost. Although SF-BIA is most used in clinical practices, this device could not predict total body water accurately. MF-BIA seems to give a better estimation of hydration than SF-BIA because the principle of measuring the flow of current through the body (impedance) is dependent on the frequency applied. At low frequencies, the current cannot bridge the cellular membrane and will pass predominantly through the extra-cellular space. At higher frequencies penetration of the cell membrane occurs and the current is conducted by both the **extra-cellular water (ECW)** and **intra-cellular water (ICW)**.⁶ However, in severely obese subjects, abnormal body geometry and water distribution may prejudice BIA accuracy of body composition estimates; the available BIA equations may not be accurate for these populations.^{7–9}

Despite these potential disadvantages, standard BIA equations are still used for estimating body composition of severely obese patients, and until now there have been no body composition equations developed specifically to predict BF in subjects with a body mass index (BMI) greater than 34 kg/m².^{6,8,10,11}

There are no methods that can be used with confidence in the severely obese subjects.³ Three-compartment models that include measurement of **total body water (TBW)** are theoretically more accurate than the two-compartment models for measuring body composition of severely obese individuals, since they take into account individual variability in hydration. The necessity of more sophisticated equipment and time-consuming tests make them available only in few research laboratories worldwide.⁵ Recently, air **displacement plethysmography (ADP)** was validated as a reference method to evaluate the body composition in severely obese subjects.¹² However, its high cost limits its clinical routine use.

Therefore, we aimed to compare the agreement of body fat estimates obtained from the standard equation used for four-frequency BIA (FourF-BIA) and ADP, and in the case of incongruity between the estimates produced by these two methods, to develop a new equation from BIA parameters for estimating BF of severely obese subjects.

Subjects and methods

Subjects

One hundred and nine severely obese preoperative gastric bypass patients participated in this study. Patients were excluded if they were younger than 18 years of age, had cancer, coronary heart disease, hepatic or pulmonary failure, chronic kidney disease, impaired thyroid function, or were pregnant or breast-feeding.

This study was developed in the Department of Gastroenterology, Surgical Division from the University of São Paulo, and the study protocol was approved by the Ethical Committee from Clinics Hospital and School of Medicine. We obtained written informed consent from each patient prior to participation in the study.

Methods

Study protocol

We interviewed all patients upon prior to enrollment in order to verify inclusion/exclusion criteria, explain instructions of the study protocol, and obtain informed consent. Patients underwent anthropometrical and body composition assessments within the following one to two weeks.

Anthropometrical assessment

The anthropometrical measurements were performed in the morning on the day of the body composition assessment, and included body weight and height determinations. Weight was measured to the nearest 0.01 kg using the ADP scale, this scale was calibrated daily using two standard 10-kg weights. Height was measured to the nearest 0.1 cm using the stadiometer, model Sanny®, with subjects standing erect without shoes.

BMI was calculated as body weight (in kg) divided by squared height (in meters).¹³

Body composition

The body composition of each patient was assessed by ADP and FourF-BIA measurements in the same day. The patients were admitted to the hospital at 07:00 h after a 12-h overnight fast. Patients had been instructed to not smoke or not drink alcohol on the day of the assessment. The same trained technician evaluated all patients.

Bioelectrical impedance analysis

The FourF-BIA body composition was obtained using multifrequency bioelectrical impedance (QuadScan 4000, Bodystat Ltda, Douglas, UK) operating at 5, 50, 100 and 200 kHz. In order to obtain the resistance, reactance and phase angle values the Phase Angle Program, BodyStat® of FourF-BIA

was used. The examination was performed according to standards of the National Institutes of Health.¹⁴

Air displacement plethysmography

Body composition was measured by air displacement plethysmography (BOD POD; Life Measurement Inc., Concord, CA, USA). Procedures for ADP have been explained in detail elsewhere.^{15,16} Briefly, before each trial, the ADP was calibrated using a 50.341-L cylinder. All subjects were tested wearing minimal, tight-fitting clothing (swimming suit or bra and panties for women and underpants for men) and swimming cap to compress the hair.^{17,18} Measured thoracic gas volume was used to calculate a corrected body volume (corrected body volume = raw body volume – thoracic gas volume). Body density was calculated as body mass divided by the corrected body volume.¹⁹ BF (in kg) was calculated as %BF multiplied by total body mass obtained on the digital scale. Fat-free mass (FFM, in kg) was calculated from body weight minus BF. The general error range of ADP is 1–2% (the same as hydrostatic weighing).

Statistical methods

The statistical analyses were performed using STATA, version 9.2 (STATA Corp, College Station, TX, USA). The results are expressed as the mean plus or minus standard deviation (SD). We used the paired *t*-test to compare the differences in BF and FFM obtained using BIA and ADP. Comparisons of body composition between gender were assessed by Student's unpaired *t*-test or Mann–Whitney *U*-test, when appropriate. The agreement between BF values from the two methods (ADP and FourF-BIA) was assessed according to the concordance correlation coefficient (CCC) and the Bland–Altman graphic.²⁰ All analyses were performed for the whole group and based on sex.

The sample was randomly separated, by statistical program, into model building (50%) and validation (50%) subsamples. A backward multivariate linear regression was used to develop two specific BF prediction equations from anthropometrics (weight, height, body mass index (BMI)) and BIA parameters (phase angle, 50 kHz resistance and reactance and 5 kHz, 50 kHz, 100 kHz and 200 kHz impedance) in the model building subsample and tested in the validation subsample. The predictor variables included were: gender, age, weight, height, BMI, phase angle, 50 kHz resistance and reactance and 5 kHz, 50 kHz, 100 kHz and 200 kHz impedance, and ADP BF was used as the dependent variable. The agreement between BF values from the ADP and the two new BF equations were assessed

Table 1 Descriptive statistics by gender and for total sample

Characteristics	All subjects (n = 119)	Male (n = 36)	Female (n = 83)
Age (years)	41.61 ± 11.61	38.51 ± 11.73	42.99 ± 11.35
Weight (kg)	126.55 ± 26.71	152.77 ± 25.10	114.86 ± 17.61
Height (cm)	163.6 ± 10.4	174.8 ± 8.2	158.7 ± 6.9
BMI (kg/m ²)	46.88 ± 6.22	49.91 ± 6.74	45.52 ± 5.49

Values are expressed as mean ± SD.

according to the concordance correlation coefficient (CCC) and the Bland–Altman graphic.²⁰ Statistical significance was set at *p* < 0.05 for all tests.

Results

Physical characteristics of the subjects

We evaluated 120 patients in this study, but one patient could not be included in the ADP assessment. Patient characteristics are shown in Table 1. Most of the patients were women (70%), BMI ranged from 34.4 to 59.6 kg/m², and age ranged from 18 to 62 years.

Comparison of BF (kg) estimated by BIA and ADP

BF estimates obtained from ADP and BIA varied from 39.0 kg to 101.1 kg and 37.2 kg to 112.7 kg, respectively. Women had a significantly greater %BF than men, although the amount of fat (in kg) was greater in men (Table 2).

A non-significant difference of –0.8 kg in BF was found between the two methods for the whole group. However, quite different results were found between BF (kg) estimations obtained by ADP and BIA when gender-specific analyses were performed. As compared to BF estimation obtained from ADP, BF (kg) obtained from BIA was overestimated (1.3 kg) in females and underestimated in males (–5.6 kg).

Data showed an excellent precision (*r*), accuracy (*Cb*), and concordance correlation coefficient (CCC) for whole group and separated by gender, as seen in Fig. 1. The Bland–Altman plots for agreement in the sample as a whole, and separated by gender, are displayed in Fig. 1. Although bias was small in the total sample, 95% CI ranges were quite wide, as seen in Fig. 1.

Table 2 Body composition determinations by ADP and BIA

Method	All subjects (n = 119)		Male (n = 36)		Female (n = 83)	
	ADP	BIA	ADP	BIA	ADP	BIA
BF (%)	51.62 ± 5.32	51.28 ± 5.77	48.98 ± 5.71 ^{a,b}	45.26 ± 5.04 ^c	52.77 ± 4.74 ^a	53.89 ± 3.78
BF (kg)	65.56 ± 16.43	64.77 ± 14.97	76.02 ± 18.99 ^{a,b}	70.44 ± 18.03 ^c	61.02 ± 12.88 ^a	62.32 ± 12.78
FFM (%)	48.45 ± 5.39	48.72 ± 5.77	51.30 ± 5.80 ^{a,b}	54.74 ± 5.04 ^c	47.22 ± 4.73 ^a	46.11 ± 3.78
FFM (kg)	60.97 ± 13.54	61.76 ± 15.69	77.34 ± 9.86 ^{a,b}	82.93 ± 8.65 ^c	53.86 ± 7.32 ^a	52.58 ± 6.34

Values are expressed as mean ± SD. ^aADP vs. BIA, *p* < 0.01; ^bADP male vs. ADP female, *p* < 0.05; ^cBIA male vs. BIA female, *p* < 0.05. BF, body fat; FFM, fat free mass; ADP, air displacement plethysmography; BIA, bioelectric impedance analysis.

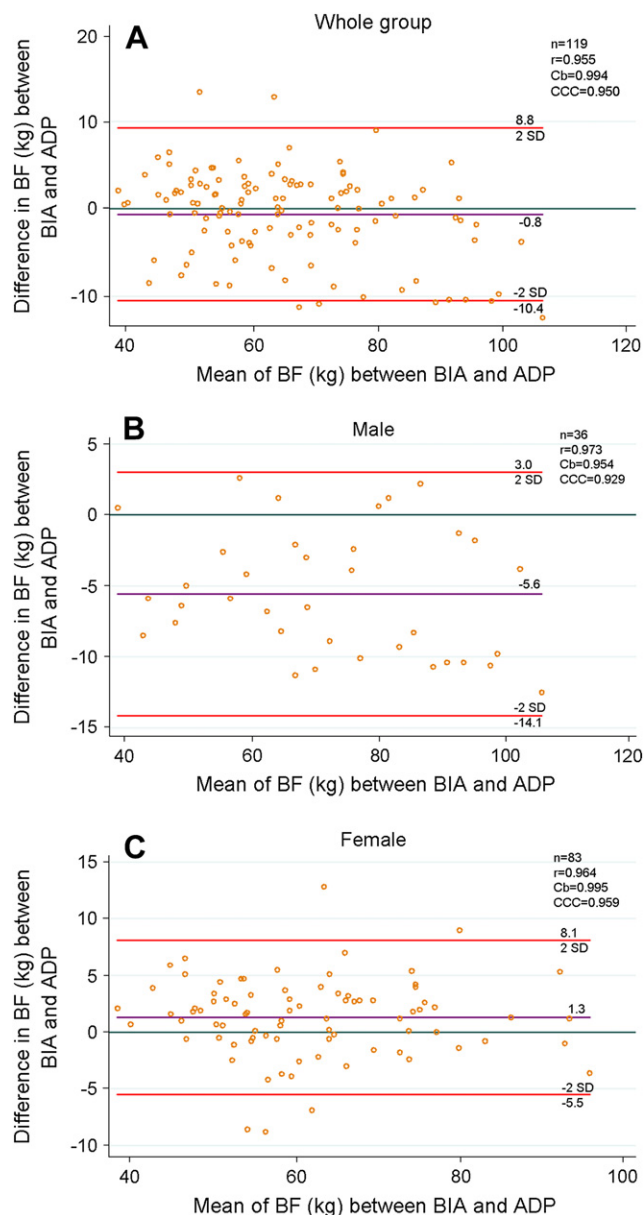


Figure 1 Bland–Altman plot showing the limits of agreement between body fat (BF) estimates made using multi-frequency bioelectrical impedance (BIA) and air displacement plethysmograph (ADP) in (A) whole group, (B) male, and (C) female. The center line represents the mean differences between the two methods, and the other two lines represent two SDs from the mean (r = precision, Cb = accuracy, CCC = concordance correlation coefficient).

Multivariate regression analysis was performed to identify the significant determinants of body fat from physical variables and MF-BIA parameters, using body fat from ADP as dependent variable.

New Horie-Waitzberg & Barbosa-Silva equations for estimating BF

The results of regression analyses developed in the model building subsample, having BF (in kg) from ADP as

Table 3 Multiple linear regression analysis using body fat (in kg) as the dependent variable

Body fat (adj $R^2 = 0.9729$)	$\beta \pm SEM$	95% CI	p -Value
Resistance (50 kHz)	0.094 ± 0.008	0.079; 0.110	<0.001
Age (years)	0.126 ± 0.0390	0.047; 0.204	0.002
Current weight (kg)	1.000 ± 0.0290	0.941; 1.056	<0.001
Height (cm)	-0.803 ± 0.067	-0.938; -0.667	<0.001
Intercept	23.250 ± 10.691	1.777; 44.724	0.03

β , unstandardized coefficient; SEM, standard error of the mean; CI, confidence interval.

a dependent variable, are presented in Tables 3 and 4. Two new prediction equations were developed from the comparison FourF-BIA and ADP data: one to be applied with data from resistance of 50 kHz BIA device (Horie-Waitzberg & Barbosa-Silva₁) and the other to be applied with data from impedance of 100 kHz BIA device (Horie-Waitzberg & Barbosa-Silva₂).

Multivariate linear regression analyses were performed to develop the regression equations. Our model shows that age, current weight, height, and resistance of 50 kHz were significant predictors of BF (in kg) and explained of 97% (adj $R^2 = 0.9729$) of the variability of BF (in kg) for resistance of 50 kHz BIA (Table 3). The regression analysis for impedance of 100 kHz BIA revealed that age, current weight, height, and 100 kHz impedance explained 97% (adj $R^2 = 0.9731$) of the variance of BF (in kg) (Table 4).

The final equations used in subsequent analyses, are presented for resistance of 50 kHz BIA and impedance of 100 kHz BIA:

Horie-Waitzberg & Barbosa-Silva₁ (HW & BS₁)

$$BF_1(\text{kg}) = 23.25 + (0.13 \times \text{age}) + (1.00 \times \text{current weight}) + (0.09 \times R_{50}) - (0.80 \times \text{height})$$

(BF = body fat, age in years, current weight in kg, R_{50} = 50 kHz resistance, and height in cm).

Horie-Waitzberg & Barbosa-Silva₂ (HW & BS₂)

Table 4 Multiple linear regression analysis using body fat (in kg) as the dependent variable

Body fat (adj $R^2 = 0.9731$)	$\beta \pm SEM$	95% CI	p -Value
Impedance (100 kHz)	0.100 ± 0.008	0.083; 0.1150	<0.001
Age (years)	0.114 ± 0.039	0.036; 0.191	0.005
Current weight (kg)	0.994 ± 0.028	0.937; 1.051	<0.001
Height (cm)	-0.800 ± 0.067	-0.934; -0.664	<0.001
Intercept	23.970 ± 10.639	2.602; 45.339	0.03

β , unstandardized coefficient; SEM, standard error; CI, confidence interval.

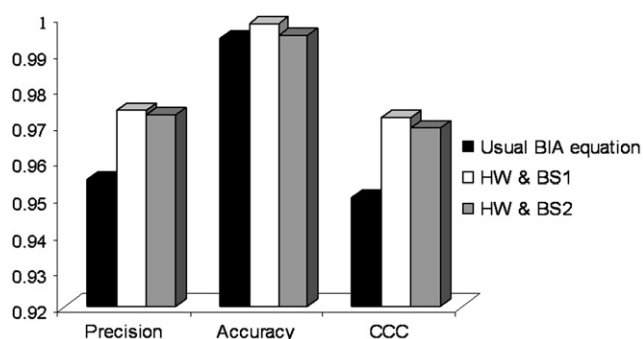


Figure 2 Comparison of BF (in kg) estimate by BIA and new predictions equations in severely obese patients. CCC = concordance correlation coefficient (precision $\times$ accuracy).

$$\text{BF}_2(\text{kg}) = 23.97 + (0.10 \times I_{100} 100) + (0.11 \times \text{age}) \\ + (0.99 \times \text{current weight}) - (0.80 \times \text{height})$$

(BF = body fat, age in years, current weight in kg, I_{100} = 100 kHz impedance, and height in cm).

The new equations were tested in the validation subsample and they showed excellent precision, accuracy, and CCC, providing better results than those obtained from the general BIA equation (Fig. 2). Furthermore, lower limits of agreement were found with the new equations, HW&BS₁ and HW&BS₂, (−7.017 to 7.884 kg and −5.919 to 8.802 kg, respectively) when compared to original general equation of FourF-BIA (−10.402 to 8.841 kg).

Discussion

Body composition assessment in severely obese patients is challenging. Few studies have measured body composition in this population.^{4,5,12,21} Petroni et al.⁴ evaluated the feasibility of ADP use for body composition assessment in the severely obese, and a more recent study validated ADP as a reference method to estimate body composition in this population.¹²

The results of our study demonstrate that BF (in kg) estimates generated using BIA and ADP did not differ when considering the sample as a whole. However, when the analysis was performed according to gender, results from BIA underestimated BF in males and overestimated BF in females. In contrast with our results, a previous study comparing BF in 46 severely obese patients obtained using BIA and underwater weighing, showed that BIA underestimated %BF in both genders (36.1% vs. 41.8% in men and 43.1% vs. 52.2% in women; $p < 0.001$).²¹ Furthermore, in our study ADP was used as reference method and BIA is multifrequency. In the Heath et al.²¹ study the reference method was underwater weighing and BIA was single frequency. These differences in the studies could lead us to different results. The exact factors causing variation in BF estimations in severely obese patients have not been identified, but we suggest some possible influencing factors in Table 5.⁷

The main keystone of using BIA as a body composition assessment method is the assumption that the FFM hydration is a constant factor, normally 73.2% in adults. Obese

Table 5 Possible causes of variability in BF estimation from BIA in severely obese subjects⁷

Violations of assumptions	Consequences of BF estimation from BIA
↑ TBW (increased FFM hydration)	↓ BF
Body build alteration (not cylindrical)	↑ BF
Relative ECW increase	↓ BF
Overall effect	↓ BF

↓ underestimation; ↑ overestimation.

BF, body fat; BIA, bioelectrical impedance analysis; TBW, total body water; FFM, fat free mass; ECW, extracellular water.

individuals are likely to have a different body water hydration as compared with lean individuals, which could modify the final results.^{3,7,8} In addition, Deurenberg²² noted that resistance was affected by the intracellular water content, varied with subject's physical activity, and may be dependent on the intracellular to total body water ratio, and hence to the intracellular to extracellular water ratio.

Das et al.⁵ performed a sophisticated BIA validation study in patients who underwent bariatric surgery. They verified that hydration (total body water) in severely obese patients was significantly higher than the reference value (0.738). The higher level of hydration in severely obese patients could lead us to overestimate FFM and, consequently, underestimate BF when using BIA. In our study, this underestimation could be found only in males, but not when the sample was analyzed as a whole or when females were analyzed alone.

There is another assumption that may not be valid when BIA is used as a body composition method for the severely obese. Body build is considered to be a cylindrical conductor,^{23,24} and it is estimated that each arm is approximately 4% of body weight and each leg is approximately 17% of body weight, but they contribute approximately 47% and 50%, respectively, to whole body resistance. The trunk contains 50% of the body mass but contributes only 5–12% of whole body resistance.^{8,25} The body build of severely obese patients is different from lean subjects. The variation of the tissue composition of the limbs and trunk may result in region-specific resistance differences^{23,26,27} and contribute to BF overestimation.

Swan and McConnell²⁸ studied the accuracy of several general anthropometric and BIA regression equations used to estimate the BF percentage in women with either upper body (UB) or lower (LB) fat distribution patterns. They hypothesized that the location of the body fat could influence the electrical conductivity differently in the UB versus the LB. This could explain the %BF differences between the genders. Thus, the authors concluded that anthropometric and some BIA equations are accurate for predicting the BF percentage in lower BF "shaped" women, but are not appropriate for women with primarily abdominal fat patterning. This different fat patterning (abdominal or not) could be the reason for the differences in BF estimation accuracy between genders.

Few studies have compared BIA and reference methods in severely obese patients, and the equations in routine

use were validated only in subjects with BMI lower than 34 kg/m^2 .^{6,8,10,11}

To our knowledge, this is the first study that compares the accuracy of ADP and multi-frequency BIA in a large sample of severely obese patients. The new predictive equations were developed to improve the accuracy of BIA for estimating body composition in severely obese patients. The standard equation used with the FourF-BIA instrument is not adequate for these individuals, our prediction equations use variables that are not influenced by hydration. Although the new regression equations did not use gender as predictor of body fat in severely obesity patients, they provided more accurate BF estimated in individual obese patients than did equations from the BIA device, as demonstrated by the Bland–Altman graphic. Variables such as weight, height, age and impedance of 100 kHz, which were included in the final model, have more importance in predicting the BF than sex. Moreover, there were more women than men in our sample. This disproportion between genders could be a possible cause for the exclusion of this variable from the final model.

The limits and expense of available methods for evaluating BF in severely obese subjects may be the reason for the low number of studies comprising the literature. This observation suggests that, in addition to the clinical relevance of predictive equations developed in this study, these equations could promote the development of new studies involving the severely obese by institutions and researchers who do not have access to reference methods such as ADP.

The limitations of the present study include the relatively small sample size and the disproportion of gender in BF equations.

In conclusion, our findings show that the standard BIA equation developed for the general population is not accurate for assessing BF in severely obese patients. However, our new equations developed especially for this population show increased accuracy when compared to the original BIA equation.

Conflict of interest statement

No conflict of interest, personal or financial, exists for any author. The authors certify that affiliation with or involvement in any organization or entity with a direct financial interest in the subject matter or materials are discussed in the Acknowledgments section below.

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and the writing of the manuscript. M.T.M. contributed to the air displacement measurements. I.C. contributed to interpretation of the results. D.L.W. contributed to the conception and design of the research, and review of the manuscript.

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