Development of a dual-energy X-ray absorptiometry-derived body volume equation in Hispanic adults for administering a four-compartment model

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Abstract

The purpose of the present study was: (1) to develop a new dual-energy X-ray absorptiometry (DXA)-derived body volume (BV) equation with the GE-Lunar prodigy while utilising underwater weighing (UWW) as a criterion and (2) to cross-validate the novel DXA-derived BV equation (4C-DXA$_{Nickerson}$), Wilson DXA-derived BV equation (4C-DXA$_{Wilson}$) and air displacement plethysmography (ADP)-derived BV (4C-ADP) in Hispanic adults. A total of 191 Hispanic adults (18–45 years) participated in the present study. The development sample consisted of 120 females and males (50 % females), whereas the cross-validation sample comprised of forty-one females and thirty males (n 71). Criterion body fat percentage (BF %) and fat-free mass (FFM) were determined using a four-compartment (4C) model with UWW as a criterion for BV (4C-UWW). 4C-DXA$_{Nickerson}$, 4C-DXA$_{Wilson}$ and 4C-ADP were compared against 4C-UWW in the cross-validation sample. 4C-DXA$_{Nickerson}$, 4C-DXA$_{Wilson}$ and 4C-ADP all produced similar validity statistics when compared with 4C-UWW in Hispanic males (all $P > 0.05$). 4C-DXA$_{Nickerson}$ also yielded similar BF % and FFM values as 4C-UWW when evaluating the mean differences (constant error (CE)) in Hispanic females (CE = –0·79 % and 0·38 kg; $P = 0.060$ and 0·174, respectively). However, 4C-DXA$_{Wilson}$ produced significantly different BF % and FFM values (CE = 3·22 % and –2·20 kg, respectively; both $P < 0.001$). Additionally, 4C-DXA$_{Wilson}$ yielded significant proportional bias when estimating BF % ($P < 0.001$), whereas 4C-ADP produced significant proportional bias for BF % and FFM (both $P < 0.05$) when evaluated in Hispanic females. The present study findings demonstrate that 4C-DXA$_{Nickerson}$ is a valid measure of BV in Hispanics and is recommended for use in clinics, where DXA is the main body composition assessment technique.

Key words: Body composition: Adiposity: Lean mass: Multi-compartment models

Addressing the health-related consequences of obesity among racial–ethnic minorities is a primary focus of Healthy People 2020, especially among Hispanic adults where the prevalence is approaching 50 % and is considerably higher than among non-Hispanic whites[1]. Further compounding the problem, Hispanic adults typically present higher body fat percentage (BF %) values than non-Hispanic black and non-Hispanic white adults, even at similar BMI values across the lifespan[2]. This is problematic since BMI-based body fat equations have been developed in non-Hispanic populations[3–5]. Despite these growing concerns and increasing obesity trends, valid and reliable body composition assessment methods in Hispanic populations are extremely scarce[6] and hence need further development.

Traditional body composition methods such as underwater weighing (UWW) and air displacement plethysmography (ADP) employ a two-compartment (2C) model approach, which divides the body into fat and fat-free masses (FM and FFM, respectively)[7,8]. A limitation of a 2C model is the assumption of FFM characteristics, which assumes that aqueous content (TBW$_{FFM}$) and bone mineral (Mo$_{FFM}$) comprise 73·8 and 5·6 %, respectively, of FFM[9]. Moreover, these assumptions are based upon three white male reference cadavers, which is problematic since body composition is known to vary between and within populations[9,10]. To reduce the potential limitations of the 2C model approach, researchers and clinicians often use a combination of body composition assessment techniques to more accurately measure the components of FFM.

Multi-compartment models, such as the four-compartment (4C) model, can more accurately measure body composition by further accounting for individual variations in total body water (TBW) and bone mineral content (BMC)[11–13]. Despite acceptance of the 4C model, the administration of this technique is not practical outside of research settings due to the need to acquire body volume (BV) via UWW or ADP (4C-UWW and 4C-ADP, respectively). The administration of UWW and ADP can be difficult for individuals who are (1) hydrophobic, (2) claustrophobic or (3) who experience mobility limitations such as elderly and obese populations[14,15]. Collectively, these issues have led to the development of alternative approaches for the measurement of BV, which include the use of dual-energy X-ray absorptiometry (DXA).

There are multiple DXA-derived BV equations available for the estimation of BV[16–18]. However, the use of a DXA-derived BV equation in a 4C model should be carefully selected, as the most commonly used DXA BV equations were developed utilising a Hologic[16,18] or a GE-Lunar Prodigy DXA scanner[17]. Previous research has shown that the two DXA BV equations derived from Hologic scanners produce significantly different body composition metrics (e.g. BF%) when employed in a 4C model[19]. Moreover, the Hologic DXA-derived BV equations yield inaccurate volume estimates when used in 4C models in participants scanned using GE-Lunar Prodigy and GE-Lunar iDXA[20,21]. These findings highlight that the DXA-derived BV equations are probably not interchangeable when utilising devices that differ from the scanner used to develop regression coefficients.

Concerns with current DXA-derived BV equations include the use of ADP as a criterion to develop each equation[16–18]. UWW has traditionally been accepted as the 'gold standard' for BV assessments[9,22,23]. Further, research has demonstrated differences between UWW and ADP for the estimation of body density (D_b) and BF%[24,25]. As a result, the error associated with ADP might be embedded in currently existing DXA-derived BV equations, which would reduce accuracy when used in a 4C model. Finally, each DXA-derived BV equation is estimated utilising the density coefficients of lean mass (LM), FM and BMC. This could potentially introduce error since recent research has shown that the FFM density (D_{FFM} = 1·105 and 1·107 g/cm³), TBW_{FFM} (72·00 and 71·88 %) and Mo_{FFM} (4·95 and 5·51 %) of Hispanic males and females, respectively, differ from the aforementioned 'reference body' of white males (1·100 g/cm³, 73·8 and 5·6 %, respectively)[10]. For these reasons, Hispanic FFM characteristics may not be comparable with the LM, FM and BMC densities obtained in validation samples for each DXA-derived BV equation, which consisted primarily of non-Hispanic whites. Therefore, the purpose of the present study was (1) to develop a new DXA-derived BV equation with the GE-Lunar prodigy ($DXA_{Nickerson}$) while utilising UWW as a criterion and (2) to cross-validate 4C-$DXA_{Nickerson}$, 4C-DXA_{Wilson}[17] and 4C-ADP in Hispanic adults.

Experimental methods

Participants

A sample of 191 Hispanic adults participated in the present study. Participant characteristics are displayed in Table 1.

Table 1. Subject characteristics for development and cross-validation sample
(Mean values and standard deviations; minimum and maximum values)

| | Development sample | | | | | | | | Cross-validation sample | | | | | | | |
| | Women (n 60) | | | | Men (n 60) | | | | Women (n 41) | | | | Men (n 30) | | | |
	Mean	SD	Minimum	Maximum	Mean	SD	Minimum	Maximum	Mean	SD	Minimum	Maximum	Mean	SD	Minimum	Maximum
Age (years)	26	8	18	45	25	7	18	44	26	7	18	45	26	7	18	45
Height (cm)	160·21	6·05	147·00	175·30	173·29	6·84	162·00	193·60	161·08	5·49	148·50	174·2	174·58	5·57	164·50	188·90
Body mass (kg)	64·92	13·01	46·00	108·80	81·92	15·40	58·20	125·10	63·69	14·18	36·30	98·70	84·12	16·31	58·20	136·30
BMI (kg/m²)	25·32	5·03	18·40	42·34	27·19	4·34	19·58	40·33	24·48	5·10	16·46	38·76	27·49	4·35	19·00	40·61
4C-UWW FFM (kg)	44·67	6·89	33·35	64·83	63·75	9·84	46·99	96·12	43·83	7·38	26·62	58·85	65·70	10·59	49·16	94·82
4C-UWW fat mass (kg)	20·25	7·86	8·17	43·97	18·17	8·96	6·67	45·69	19·86	8·44	9·13	42·59	18·42	8·09	7·24	41·48
4C-UWW body fat %	30·40	6·74	15·16	44·11	21·37	7·58	8·71	37·98	30·25	6·76	17·98	43·69	21·29	6·14	10·03	32·02
UWW D_b (g/cm³)	1·03	0·02	1·01	1·07	1·05	0·02	1·01	1·09	1·03	0·02	1·01	1·07	1·05	0·02	1·02	1·08
ADP D_b (g/cm³)	1·04	0·02	1·00	1·09	1·06	0·02	1·00	1·09	1·04	0·02	1·00	1·08	1·05	0·02	1·02	1·09
TBW (litres)	31·78	4·93	22·50	43·68	45·83	6·97	33·02	68·43	31·40	5·51	18·28	41·71	47·36	8·39	33·37	70·17
TBW/FFM (%)	71·55	2·30	65·01	76·87	71·95	2·35	65·01	76·87	71·62	3·82	67·60	79·57	71·96	2·60	67·32	78·33
BMC (kg)	2·33	0·28	1·82	2·88	3·03	0·47	2·19	4·30	2·27	0·35	1·50	3·08	3·05	0·40	2·50	3·87
BMC/FFM (%)	5·02	0·52	3·96	6·68	4·77	0·42	3·96	5·81	5·22	0·56	4·16	6·30	4·67	0·36	4·08	5·45
UWW BV (litres)	62·91	13·27	43·91	107·06	78·11	15·54	54·51	119·61	61·78	14·43	35·05	97·46	80·23	16·49	54·09	133·01
ADP BV (litres)	62·89	13·61	43·95	109·20	77·77	15·73	53·64	120·11	61·71	14·74	34·37	98·42	80·05	16·57	53·58	132·59
DXA BV_{Wilson} (litres)	63·64	13·69	44·25	109·39	78·23	15·50	54·57	119·49	62·58	14·95	35·49	100·95	80·57	16·89	54·13	135·09
DXA $BV_{Nickerson}$ (litres)	–	–	–	–	–	–	–	–	61·64	14·64	34·67	99·09	80·19	16·72	54·08	134·15

4C, four-compartment model; UWW, underwater weighing; FFM, fat-free mass; D_b, body density; ADP, air displacement plethysmography; TBW, total body water; BMC, bone mineral content; BV, body volume; DXA, dual-energy X-ray absorptiometry.

A sample of 120 participants (50 % females) was randomly selected to develop the coefficients reported in Equation 1. The remaining sample of seventy-one participants (females: 41; males: 30) was utilised as a cross-validation sample. Eligible participants were (1) adults between 18 and 45 years of age, (2) self-reported Hispanic ethnicity, (3) were apparently healthy with no self-reported medical conditions that would impact body composition assessments (e.g. dialysis treatment) and (4) <350 lbs (159 kg) due to DXA table restrictions. Pregnant women and those who were pregnant within the previous 12 months were also excluded from the present study. All body composition assessment measurements were performed on the same day during a single visit that lasted approximately 90–120 min. Participants were asked to avoid eating or drinking 12 h prior to participation and to also avoid exercise 24 h before testing. Testing times occurred in the morning from 06.00 to 10.00 hours. Prior to testing, participants provided written informed consent and completed a self-reported medical history questionnaire. The present study was approved by the Institutional Review Board of the host university.

Procedures

Upon completion of the informed consent and medical history questionnaire, participants' hydration status was assessed from a urine sample using a handheld refractometer (Atago SUR-NE; Atago Corp. Ltd). Urine specific gravity values <1·029 were required for participation[26]. After confirming adequate hydration, body mass was measured (to the nearest 0·1 kg) with a calibrated digital weighing scale (Tanita BWB-800; Tanita Corporation), whereas height was measured to the nearest 0·1 cm with a stadiometer (SECA 213; Seca Ltd).

Dual-energy X-ray absorptiometry

DXA (2016 GE-Lunar Prodigy, enCORE v17; GE Lunar Corporation) was used to measure LM, FM and BMC in order to develop the coefficients for the new DXA-derived BV equation and to estimate BV via the Wilson[17] equation. Prior to each whole-body scan, DXA was calibrated according to the manufacturer's instructions via a standard calibration block. Participants removed shoes, socks and all jewellery and were instructed to lie supine on the scanning bed with hands by the sides. During all body scans, participants were asked to remain motionless, while Velcro straps were situated around the ankles and knees. Scans lasted approximately 6–10 min. The same researcher positioned all participants on the DXA scanning bed. In addition, the trained researcher analysed each scan to adjust software-determined regions of interest prior to producing the whole-body report. Finally, the prediction equation (Eq. 2) proposed by Wilson[17] was used to estimate BV for 4C-DXA$_{Wilson}$. The symbol V represents the volumetric densities of fat, lean soft tissue and BMC, whereas the coefficient $V_{Residual}$ represents the residual volume that the three DXA mass compartments do not fully capture in the estimate of total BV.

$$DXA\ volume\ (litres) = (FM/V_{Fat}) + (LM/V_{Lean}) + (BMC/V_{BMC}) + V_{Residual} \quad (1)$$

Wilson equation[17]:

$$DXA\ volume\ (litres) = (FM/0·87) + (LM/1·072) - (BMC/2·283) + 1·504 \quad (2)$$

DXA was also used to calculate BMC for all 4C models. The total body BMC was converted to total body bone mineral (Mo). Mo was calculated as follows: Mo = total body BMC (kg) × 1·0436[27].

Bioimpedance spectroscopy

Bioimpedance spectroscopy was used to determine TBW (Imp^{TM} SFB7; ImpediMed Limited) for all of the 4C models evaluated in the present study. Bioimpedance spectroscopy testing occurred immediately after DXA scans since assessments for the bioimpedance spectroscopy device require participants to lay a minimum of 5 min prior to measurements. The velcro straps were removed following the DXA scan to allow for proper placement during the bioelectrical impedance analysis (BIA) measurement. Also following the DXA scan, excess hair was removed and the skin was cleaned with alcohol pads and dried prior to the BIA measurements at each of the electrode sites to ensure proper conduction of the electrical currents. The participants' right shoe and sock remained off, and their arms placed ≥30° away from the body with legs separated and not touching. Two single tab electrodes were placed at the distal end of the participant's (1) right wrist and hand and (2) right ankle and foot, with 5 cm between each set of electrodes in order to measure TBW.

Air displacement plethysmography

The BOD POD® (COSMED USA Inc.) was used to estimate BV for 4C-ADP in the cross-validation sample. Prior to each testing day, the BOD POD® was calibrated according to manufacturer specifications. Participants were required to wear minimal, lycra compression clothing, and lycra swim-caps were provided and required for testing. Body mass was measured using the manufacturer's scale that interfaces with the BOD POD®. In order to assess BV, participants were instructed to sit in the BOD POD® chamber for two trials of roughly 50 s for each trial. A third trial was necessary if the first two trials did not agree within 150 ml of each other. Thoracic gas volume was estimated for all assessments.

Underwater weighing

UWW was performed in an apparatus specifically designed for densitometry measurements (Vacu-Med). The BV measurement obtained in the development sample was used as the criterion variable in order to develop the new DXA-derived BV equation. In addition, UWW-derived BV was used to calculate 4C-UWW BF % and FFM in the cross-validation sample. All UWW tests

were performed last due to the impact that a warm water temperature could have on body temperature. Water temperature for testing was approximately 35–38°C for all participants. Furthermore, each UWW test lasted approximately 10–15 min for participants. Prior to the UWW measurements, participants changed into compression type clothing or a bathing suit. Participants sat on a sling seat during testing. The participants were instructed to perform a maximum expiration and submerge completely underwater. Prior to all UWW testing, residual lung volume was completed using a nitrogen analyser on dry land in a seated position (Vacu-Med).

Four-compartment model calculation

The 4C model is based upon the equation described by Wang *et al.*[28] and is described as follows:

$$FM\,(kg) = 2{\cdot}748(BV) - 0{\cdot}699(TBW) + 1{\cdot}129(Mo) - 2{\cdot}051(BM)$$
$$FFM\,(kg) = (BM - FM)$$
$$BF\% = (FM/BM) \times 100$$

$$(3)$$

Statistical analyses

Multivariate linear regression using the enter method was used to derive the new DXA-derived BV equation in the development sample. Data were screened for outliers and normal distribution with skewness or kurtosis >2 indicating non-normal distribution[29]. Distributions of all independent variables from the DXA scan (FM, LM and BMC) and variables used in the 4C model (BMC, TBW, UWW-derived BV, 4C-ADP, 4C-DXA$_{Wilson}$, 4C-DXA$_{Nickerson}$ and 4C-UWW) were normal. The BV from UWW was used as the dependent variable, and FM, LM and BMC from DXA were used as independent factors in order to derive the coefficients in Eq. (1). The new coefficients were subsequently utilised to calculate DXA-derived BV in the cross-validation sample in order to determine the accuracy of the new equation in a 4C model for the estimation of BF% and FFM in Hispanic adults.

The validity of 4C-ADP, 4C-DXA$_{Wilson}$ and 4C-DXA$_{Nickerson}$ was based upon comparisons with the 4C-UWW by calculating the constant error, *r* value, standard error of estimate, total error (TE) and proportional bias[30,31]. The mean differences in BF% and FFM (i.e. constant error) among the 4C models were compared with the 4C-UWW (e.g. 4C-DXA$_{Nickerson}$ − 4C-UWW) and analysed using dependent *t* tests (SPSS version 24) with the Bonferroni-adjusted α level ($P \leq 0{\cdot}0166$). Differences between the UWW criterion, ADP and DXA measures were assessed using a standardised mean effect size (ES), by dividing the difference between the criterion and alternative measure by the standard deviation of the criterion. Threshold values for the standardised ES were 0·2, 0·5 and 0·8 for small, moderate and large differences, respectively[32]. The following thresholds were used to describe the *r* values: 0–0·30 small, 0·31–0·49 moderate, 0·50–0·69 large, 0·70–0·89 very large and 0·90–1·00 near-perfect[33]. The method of Bland–Altman was used to identify the 95 % limits of agreement (LOA) of the 4C models[34]. An *a priori* power analysis was performed using G*power (version 3.1.9.3) and indicated that thirty-four participants were needed in order to detect a moderate

difference between two body composition assessment methods (power = 0·80, α level = 0·05)[35,36].

Results

Participants were aged 18–45 years (25·74 (SD 7·15) years) and mostly female (53·1 %). Standing height ranged from 147·00 to 193·60 cm (166·76 (SD 8·98) cm), and weight ranged from 36·30 to 136·30 kg (73·01 (SD 17·12) kg). Finally, BMI ranged from 16·46 to 42·34 kg/m² (26·07 (SD 4·84) kg/m²), with 37·69 and 18·23 % of the sample classified as overweight and obesity, respectively. Additional participant characteristics for the development and cross-validation samples are stratified by sex and presented in Table 1.

Body volume equation

The inverse of the density coefficients of FM, LM and BMC determined for the new DXA-derived BV equation was 0·91 ($P < 0{\cdot}001$), 1·06 ($P < 0{\cdot}001$) and 16·95 ($P = 0{\cdot}841$), respectively, with a residual volume of 0·268 litres.

$$DXA_{Nickerson}\ volume\ (litres) = (FM/0{\cdot}91) + (LM/1{\cdot}06)$$
$$+ (BMC/16{\cdot}95) + 0{\cdot}268 \quad (4)$$

Body fat percentage

The validity of 4C-DXA$_{Wilson}$, 4C-DXA$_{Nickerson}$ and 4C-ADP when compared with 4C-UWW is displayed in Table 2. Small non-significant differences were observed in the cross-validation sample of females (ES = –0·12, $P = 0{\cdot}06$) and males (ES = –0·04, $P = 0{\cdot}61$), when evaluating the 4C-DXA$_{Nickerson}$. Similarly, small non-significant differences were observed with the 4C-ADP in the cross-validation sample of females (ES = –0·08, $P = 0{\cdot}12$) and males (ES = –0·11, $P = 0{\cdot}05$). Contrarily, 4C-DXA$_{Wilson}$ yielded a moderate difference when compared with 4C-UWW in females (ES = 0·48, $P < 0{\cdot}001$), but not in males (ES = 0·15, $P = 0{\cdot}06$). Near-perfect correlation coefficients were observed for all methods when evaluated in both sexes, as observed *r* values ranged from 0·903 to 0·961. The TE was lowest for 4C-ADP in both sexes and was fairly similar between 4C-DXA$_{Wilson}$ and 4C-DXA$_{Nickerson}$ in males, whereas the 4C-DXA$_{Nickerson}$ equation performed better in females. No proportional bias was observed in males for any of the comparisons, as the correlations ranged from –0·03 to 0·13 (all $P > 0{\cdot}05$). However, 4C-DXA$_{Nickerson}$ was the only prediction method that did not produce significant proportional bias when evaluated in females (*r* 0·11, $P = 0{\cdot}071$). The significant proportional bias coefficients observed for 4C-ADP (*r* 0·19) and 4C-DXA$_{Wilson}$ (*r* 0·23) in females indicate that BF% is overestimated at higher 4C-UWW adiposity levels (both $P < 0{\cdot}001$). Fig. 1 displays the Bland–Altman plots (i.e. 95 % LOA) and proportional bias (i.e. trend line) for all BF% measurements.

Fat-free mass

The mean values were not statistically significant in the cross-validation sample of females (ES = 0·05, $P = 0{\cdot}174$) and males (ES = 0·01, $P = 0{\cdot}812$), when evaluating the 4C-DXA$_{Nickerson}$.

Table 2. Validation of dual-energy X-ray absorptiometry (DXA)- and air displacement plethysmography (ADP)-derived body volume (BV) in cross-validation sample of females (n 41) and males (n 30) when using a four-compartment (4C) model
(Mean values and standard deviations)

Method	Mean	SD	r	SE of estimate	P	Total error	Constant error	1·96 SD	Upper	Lower	Slope	P
							Bland–Altman analysis				Proportional bias	
Women BF %												
4C-DXA$_{Wilson}$	33·47	8·42	0·937	2·39	<0·001	4·48	3·22	6·18	9·40	–2·96	0·226	<0·001
4C-DXA$_{Nickerson}$	29·46	7·50	0·938	2·37	0·060	2·70	–0·79	5·11	4·32	–5·90	0·106	0·071
4C-ADP	29·67	7·89	0·961	2·21	0·124	2·38	–0·57	4·58	4·01	–5·16	0·188	<0·001
4C-UWW	30·25	6·76	–	–	–	–	–	–	–	–	–	–
Men BF %												
4C-DXA$_{Wilson}$	22·23	6·93	0·903	2·33	0·060	2·73	0·93	5·11	6·04	–4·18	0·126	0·094
4C-DXA$_{Nickerson}$	21·04	5·99	0·903	2·69	0·609	2·65	–0·25	5·25	5·00	–5·50	–0·026	0·762
4C-ADP	20·62	6·26	0·956	1·86	0·053	1·92	–0·67	3·59	2·92	–4·27	0·020	0·729
4C-UWW	21·29	6·14	–	–	–	–	–	–	–	–	–	–
Women FFM (kg)												
4C-DXA$_{Wilson}$	41·63	6·88	0·942	2·51	<0·001	3·29	–2·20	4·86	2·66	–7·06	–0·071	0·204
4C-DXA$_{Nickerson}$	44·21	7·09	0·971	1·79	0·174	1·79	0·38	3·48	3·86	–3·09	–0·040	0·312
4C-ADP	44·01	6·79	0·983	1·25	0·420	1·42	0·18	2·79	2·97	–2·61	–0·084	0·007
4C-UWW	43·83	7·38	–	–	–	–	–	–	–	–	–	–
Men FFM (kg)												
4C-DXA$_{Wilson}$	64·77	9·75	0·971	2·56	0·058	2·70	–0·93	5·05	4·12	–5·97	–0·083	0·078
4C-DXA$_{Nickerson}$	65·81	9·77	0·972	2·53	0·812	2·50	0·11	4·98	5·09	–4·86	–0·081	0·082
4C-ADP	66·18	10·29	0·990	1·50	0·090	1·58	0·49	2·99	3·48	–2·50	–0·028	0·312
4C-UWW	65·70	10·58	–	–	–	–	–	–	–	–	–	–

BF %, body fat percentage; UWW, underwater weighing; FFM, fat-free mass.

Similarly, 4C-ADP yielded small mean differences when evaluated in the cross-validation sample of females (ES = 0·02, P = 0·420) and males (ES = 0·05, P = 0·090). Contrarily, 4C-DXA$_{Wilson}$ yielded a moderate difference compared with 4C-UWW when evaluated in females (ES = –0·30, P < 0·001), but not in males (ES = –0·09, P < 0·058). Near-perfect correlation coefficients were observed for all methods when evaluated in both sexes, as observed r values ranged from 0·942 to 0·990. The TE was lowest for 4C-ADP in both sexes and was fairly similar between 4C-DXA$_{Wilson}$ and 4C-DXA$_{Nickerson}$ in males. In contrast, the 4C-DXA$_{Nickerson}$ performed better than the 4C-DXA$_{Wilson}$ in females. The 4C-ADP was the only method that produced significant proportional bias when evaluating FFM. Specifically, a negative coefficient was observed in females, which indicates that FFM is underestimated at higher levels. Fig. 2 displays the Bland–Altman plots (i.e. 95 % LOA) and proportional bias (i.e. trend line) for all FFM measurements.

Discussion

All three methods (i.e. 4C-DXA$_{Wilson}$, 4C-DXA$_{Nickerson}$ and 4C-ADP) appear to be interchangeable with 4C-UWW when used in a group of apparently healthy Hispanic males. Nonetheless, due to the lower constant error and TE values, 4C-DXA$_{Nickerson}$ is recommended over the 4C-DXA$_{Wilson}$ in Hispanic males when 4C-ADP and 4C-UWW are not practical or available. In addition, the 4C-DXA$_{Nickerson}$ performed better than the 4C-DXA$_{Wilson}$ when evaluating BF % and FFM in Hispanic females. Lastly, these findings demonstrate that sex and level of fatness may impact the accuracy of 4C-ADP and 4C-DXA$_{Wilson}$, but that 4C-DXA$_{Nickerson}$ is able to overcome these issues.

The present study results advance previous work. For instance, Nickerson et al.[37] found larger standard error of estimates (3·9–4·2 %) and 95 % LOA (±7·9–8·2 %) than the present study when estimating 4C model BF % with the DXA-derived BV equation from Smith-Ryan et al.[16] in a group of physically active men and women. In contrast, Blue et al.[38] evaluated a group of overweight and obese individuals and revealed that the DXA-derived BV equation from Smith-Ryan et al.[16] produced similar TE values (2·92 %) as many of the comparisons observed in the present study. The reason for the differences between Nickerson et al.[37] and Blue et al.[38] could be related to the criterion measurements utilised to determine BV in the criterion 4C model. For instance, Nickerson et al.[37] incorporated UWW-derived BV in their criterion 4C model, whereas Blue et al.[38] and Smith-Ryan et al.[16] used ADP as a criterion when assessing the validity of their DXA-derived BV equation. Due to these differences, it is not surprising to see the DXA-derived BV equation perform better for Blue et al.[38] than Nickerson et al.[37]. Furthermore, the observed differences in the relative accuracy of the DXA-derived BV equations may be due to the study populations in which they were developed when considering the (1) population differences in FM, FFM and bone mineral density in blacks, Hispanics and whites[39,40], (2) coupled with the age-related increase in FM, decrease in total FFM and decrease in the relative contribution of BMC as a
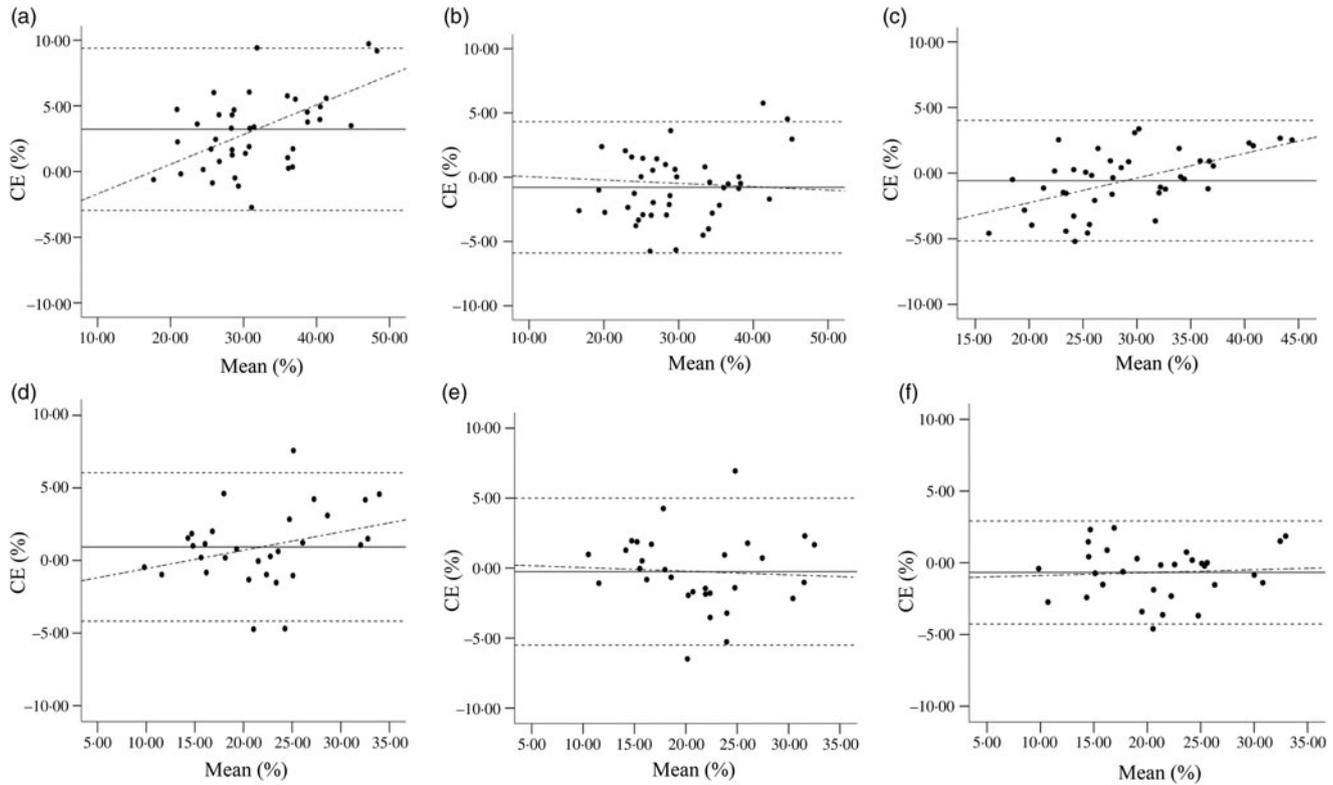
Fig. 1. Bland–Altman plot for body fat percentage (BF %) in Hispanic females and males. The middle solid line represents the constant error (CE) between the four-compartment (4C) prediction models (4C-DXA$_{Wilson}$, 4C-DXA$_{Nickerson}$ and 4C-ADP) and the criterion 4C-underwater weighing (UWW). The two outside dashed lines indicate the 95 % CI of the bias (difference) and their means. The dashed–dotted line represents the linear regression fit line. Separate Bland–Altman plots depicting BF % in the 4C prediction models are displayed for (a) 4C-DXA$_{Wilson}$ in females; (b) 4C-DXA$_{Nickerson}$ in females; (c) 4C-ADP in females; (d) 4C-DXA$_{Wilson}$ in males; (e) 4C-DXA$_{Nickerson}$ in males and (f) 4C-ADP in males. DXA, dual-energy X-ray absorptiometry; ADP, air displacement plethysmography.

fraction of FFM[41,42] and (3) changes in FFM characteristics for physically active individuals[43,44].

McLester *et al.*[20] advanced these findings and found that the Hologic DXA-derived BV equation from Smith-Ryan *et al.*[16] produced larger 95 % LOA than the Wilson *et al.*[18] equation when used in a 4C model for individuals with varying BMI and waist circumference values. Further, both Hologic DXA-derived BV equations produced proportional bias for many comparisons[16,18]. The findings observed by McLester *et al.*[20] are similar to the present study, which revealed that the GE-Lunar Prodigy DXA-derived BV equation from Wilson *et al.*[17] produced significant proportional bias when evaluated in the cross-validation sample of Hispanic females. There appears to be little physiological reason why the Wilson equation would yield such poor accuracy solely because of sex. Given that BF % among female participants in the present study was roughly 10 % higher than among male participants, it is more likely that the observed bias is due to the sex-related differences in BF % and poor accuracy in obese individuals. Nonetheless, the new DXA-derived BV equation was able to overcome these limitations and produced small constant errors, standard error of estimates, TE and 95 % LOA in addition to the absence of proportional bias. Whether the superior performance is due to biological sex or body composition, allied health professionals are encouraged to adopt the new DXA-derived BV equation for Hispanic adults when assessing body composition with a modified 4C model (i.e. DXA-derived BV and BMC; bioimpedance spectroscopy-derived TBW).

This is the first study to utilise three different laboratory-based BV measures in a multi-compartment model (i.e. UWW, ADP and DXA) at the same time point. Nickerson *et al.*[21] compared various modified 3C models using skinfold- (i.e. D$_b$/body mass), DXA- and UWW-derived BV and revealed that the aforementioned methods, when used in a multi-compartment model, improve upon stand-alone DXA body composition assessments. The findings from Nickerson *et al.*[21] demonstrate the importance of accounting for TBW in a multi-compartment model, which is unaccounted for in a stand-alone DXA body composition output. Nonetheless, prior to our findings, previous DXA-derived BV research could only be generalised to a single criterion BV reference being utilised for analysis (i.e. ADP or UWW). The present study utilised UWW instead of ADP as a reference in the 4C model since it has traditionally been regarded as the 'gold standard' for BV assessments and has yet to be utilised for the derivation of a DXA-derived BV equation[9,22,23]. The authors believe that the strength of the present study is bolstered by the use of the UWW criterion for measuring BV. However, it is unclear how the choice of a criterion measure (UWW *v.* ADP) impacted the development of the DXA$_{Nickerson}$ equation. Given that the size of the observed differences between the BF % measures comparing the 4C-DXA$_{Nickerson}$ and 4C-ADP estimates of BF % and FFM appeared to be
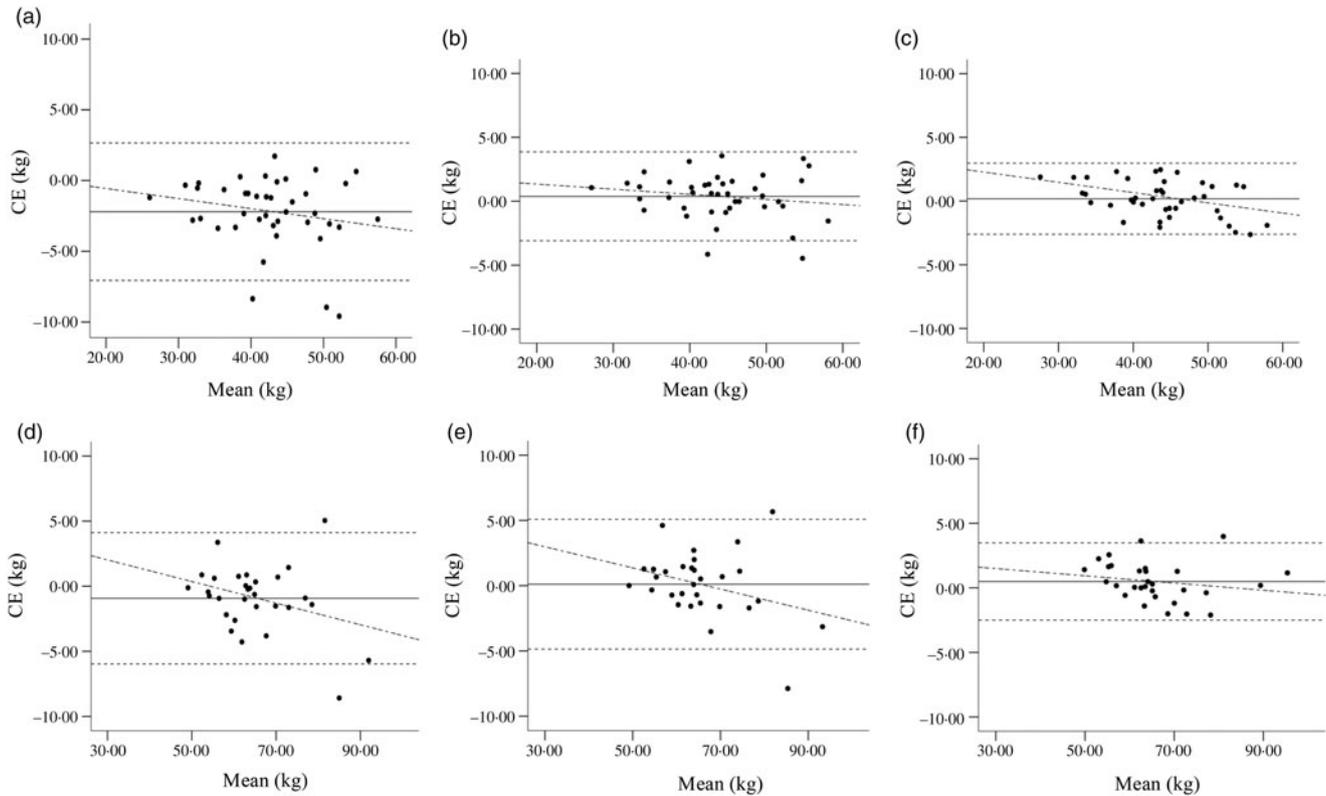
Fig. 2. Bland–Altman plot for fat-free mass (FFM) in Hispanic females and males. The middle solid line represents the constant error (CE) between the four-compartment (4C) prediction models (4C-DXA$_{Wilson}$, 4C-DXA$_{Nickerson}$ and 4C-ADP) and the criterion 4C-underwater weighing (UWW). The two outside dashed lines indicate the 95 % CI of the bias (difference) and their means. The dashed–dotted line represents the linear regression fit line. Separate Bland–Altman plots depicting FFM in the 4C prediction models are displayed for (a) 4C-DXA$_{Wilson}$ in females; (b) 4C-DXA$_{Nickerson}$ in females; (c) 4C-ADP in females; (d) 4C-DXA$_{Wilson}$ in males; (e) 4C-DXA$_{Nickerson}$ in males; (f) 4C-ADP in males. DXA, dual-energy X-ray absorptiometry; ADP, air displacement plethysmography.

negligible, it is doubtful that the use of an ADP criterion to derive each of the density coefficients would have drastically changed the results. Determining the impact of criterion choice (UWW $v.$ ADP) on subsequent density coefficients when developing a novel DXA volume equation, and the subsequent accuracy of each equation in cross-validation studies, provides an interesting opportunity for future research but was beyond the scope of the present study.

Uniquely, the present study demonstrates that the GE-Lunar Prodigy DXA-derived BV equation from Wilson et al.[17] produces similar proportional bias as ADP-derived BV in a 4C model when evaluated in Hispanic males and females. Contrarily, the new DXA-derived BV equation was unaffected and did not produce proportional bias for any comparisons. The reason for the difference could be attributed to a number of different factors worth discussion. For instance, the GE-Lunar Prodigy DXA-derived BV equation from Wilson et al.[17] was developed using ADP as a criterion measure. In addition, Wilson et al.[17] utilised a retrospective analysis of clinical patients aged 10–89 years with chronic renal disease, intestinal failure, anorexia, malnutrition, obesity, liver disease, metabolic disorders and others, whereas the present study sample consisted of apparently healthy Hispanic adults 18–45 years of age. It is commonly understood that conditions such as anorexia[45], malnutrition[46,47] and metabolic disorders[48] negatively impact bone health. As such, equations derived from a sample of clinical patients may be

inaccurate when applied to the general population. In addition, the ethnicity of participants for the Wilson et al.[17] study was not disclosed. However, given the geographical location of the study site (i.e. Melbourne and Australia) for Wilson et al.[17], it is logical that the group of Hispanics in the present study differed greatly from the former study population.

The LM coefficient for the new DXA-derived BV equation is fairly similar to the Wilson et al.[17] equation. However, there are noticeable differences in the intercept as well as the FM and BMC coefficients. In regard to the latter, BMC was a significant predictor ($P < 0.001$) of DXA-derived BV for Wilson et al.[17], which differs from the present study findings, which revealed that BMC was not statistically significant ($P = 0.841$). The present study findings are similar to results obtained by Smith-Ryan et al.[16] who also found that BMC was not statistically significant ($P = 0.853$) when developing a DXA-derived BV equation with a Hologic DXA scanner. The reason for similarities between the present study and Smith-Ryan et al.[16] is likely because both populations were apparently healthy. BMC has minimal variation in apparently healthy populations. Contrarily, there can be large BMC differences in diseased and older populations[44] such as those included in the Wilson et al.[17] study sample. Interestingly, Mo$_{FFM}$ was similar for all groups (i.e. 4·7–5·2 %) in the present study but varied from the assumed values employed in 2C models (i.e. 5·6 %), which are based upon analysis of non-Hispanic white males. Therefore, the small,

but consistent, amount of FFM that is comprised of BMC in our Hispanic population appears to have minimal benefit when used for the estimation of BV. Thus, further research utilising populations with varying BMC is warranted.

Additional considerations for the present study findings are in need of further discussion. For instance, Wilson *et al.*[17] noted that all DXA scans were made using the medium-thickness scan mode. This could have introduced bias when scanning thin or overweight/obese participants in the present study. For instance, the DXA model used in the present study has three different scan modes (i.e. thin, standard and thick), which is automatically selected by the software based upon each subject's physical characteristics. Therefore, the use of a standard scan mode for all participants is not appropriate. For example, a standard scan mode for participants with excessive adiposity, especially some of those in the present study who had BMI values classified as obese (BMI $\geq$ 30 kg/m^2), would likely have produced different regression coefficients. This might be why there was proportional bias for 4C-DXA$_{Wilson}$ when assessing the Hispanic female participants with higher BF% values, which further highlights that the level of fatness may have impacted the validity of the Wilson *et al.*[17] DXA-derived BV equation.

While this study was carefully designed and executed, it is not without limitations. First, a sample of apparently healthy Hispanic adults limited to the ages of 18–45 years served as the development population. Therefore, results cannot be applied to older Hispanic adults or those with significant health issues. Similarly, it is unknown whether the new DXA-derived BV equation can be generalised in ethnicities that differ from our Hispanic sample. Accordingly, further validation research is warranted to determine whether the 4C-DXA$_{Nickerson}$ can be applied to populations that differ from the present study sample. It should also be noted that the volume coefficients were developed using measurements from a GE Prodigy model. Aside from the age, sex, race and training status, the specific DXA model should also be considered when examining these results in the context of the larger body of research. This equation should be extensively validated in other DXA models in female and male participants, representing various racial–ethnic groups across the lifespan. Lastly, the present study sought to use only data from Hispanic adults to develop and validate the new DXA-derived BV equation. Ethnicity in the present study was self-reported, and it is unclear how much potential error was introduced by a participant identifying as Hispanic ethnicity despite no Hispanic/Latino ancestry. The authors are unaware of any such instances in the present study, but the possibility of an inaccurate or misleading participant response still exists.

In conclusion, all three methods are valid for the estimation of BF% and FFM in apparently healthy Hispanic males. 4C-ADP produced the lowest TE values, while 4C-DXA$_{Nickerson}$ produced slightly better coefficients than 4C-DXA$_{Wilson}$. These findings highlight that DXA can be used as a surrogate of ADP in a 4C model for Hispanic males. However, 4C-DXA$_{Nickerson}$ was the best method when evaluating BF% and FFM in the group of Hispanic females due to the bias observed in 4C-ADP and 4C-DXA$_{Wilson}$. For instance, 4C-DXA$_{Wilson}$ produced significant mean differences for BF% and FFM and had significant proportional bias when estimating FFM, whereas 4C-ADP

revealed significant proportional bias for both BF% and FFM when evaluated in Hispanic females. Collectively, the present study findings demonstrate that 4C-DXA$_{Nickerson}$ is a valid measure in Hispanic females and males and is recommended for use in clinics, where DXA is the main body composition assessment technique.

Supplementary material

For supplementary material referred to in this article, please visit https://doi.org/10.1017/S0007114520000598

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