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Original Article

Body fat assessment techniques: is there a place for 3D body scanners?

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Abstract

Body composition is an important domain for health, as high body fat percentages (BF%) are associated with mortality. BF% also is an important metric for athletic / sport performance and rehabilitation progress. Common BF% estimation tools include skinfold equations like Jackson-Pollock (JP7) or DXA criterion (DC), body volume measures from BODPOD or hydrostatic weighing, and dual-energy x-ray absorptiometry (DXA), which is often considered a new reference criterion. The Size Stream Body Scanner was developed by the apparel industry and generates measures such as circumferences and diameters that could be used to assess BF% in a similar manner to BODPOD. This cross-sectional study enrolled 134 adults aged between 18-62 years to develop a novel BF% estimation equation for the Size Stream Body using LASSO regression and compared it to the BF% estimates of three two component (2C) models and one three component (3C) model. The 2C models were skinfolds using the JP7 and DC equations and the BODPOD. The 3C model used as the reference standard was DXA. Agreement to DXA BF% estimates was assessed using three methods. First, a one-way ANOVA with Bonferroni post-hocs. Second, intraclass correlation coefficients (ICC) with a two-way mixed model and absolute agreement required were calculated. Lastly, Bland-Altman analyses were used to compare each assessment to DXA BF% estimates. The JP7 underestimated BF% compared to all other assessments and had the lowest ICC, followed by BODPOD (both ICCs ≤ 0.845). DC and Size Stream had excellent ICCs with values ≤ 0.944. Lastly, the female DC equation and both Size Stream equations passed the Bland Altman test for agreement with DXA BF%. These data demonstrate Size Stream may be a suitable new body composition assessment tool that is more accessible to athletes, coaches, and sports medicine professionals compared to DXA.

Keywords: body composition; Size Stream; DXA; BODPOD; Skinfolds

Introduction

Body mass index (BMI) is the most common metric for the classification of obesity. A BMI of ≥ 30 kg/m^2 is considered obese and BMIs > 35 kg/m^2 and > 40 kg/m^2 are considered severe and morbid obesity, respectively. BMI is widely employed in part due to its ease of use and strong associations with mortality for populations, but is not a measure of individual body composition or more specifically body fat percentage (BF%) and can misclassify individuals (Franco et al., 2016). This misclassification can be dangerous as many individuals may present with normal BMI but have comorbidities associated with excess adiposity such as metabolic syndrome or cardiovascular disease; this concept is called normal-weight obesity (Franco et al., 2016). Body composition and the degree of adiposity is an important indicator of health status, and many assessment techniques exist today for its quantification.

Body composition assessments can be characterized based on the number of compartments it measures/estimates. The two-compartment model (2C) of body composition stratifies the body into fat mass and fat-free mass. Skinfolds, hydrostatic weighing, and the BODPOD are examples of popular 2C models. 3C models would measure bone mineral, bone free lean body mass, and adipose (fat) with dual-energy x-ray absorptiometry (DXA) being the most common option. The 4C model requires measurement of total body weight, volume, water, and bone mineral and is considered the most accurate methodology for BF% estimation (Toombs et al., 2012).

Many factors go into deciding what methodology to use such as cost, time, accessibility, accuracy, and precision. 2C models are the most common assessment type because they are often cheap, fast, and easy to administer but have lower cited accuracy and precision values compared to 3C and 4C models (Lee & Gallagher, 2008). 4C models have been cited as the most accurate but require multiple tests from specialized laboratory equipment potentially reducing the inter-tester reliability and accessibility to non-academic entities (Friedl et al., 1992). For these reasons many now consider DXA to be the new reference criterion for body composition assessment as the method is highly accurate, precise, and only takes three minutes to complete on newer models

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(Bilsborough et al., 2014; Norcross & Van Loan, 2004; Shepherd et al., 2017). Although DXA's popularity has skyrocketed in the past 20 years (Baker, Li, & Leary, 2021), 2C models remain the most commonly used methods due to their cheap and fast nature. Burns, Fu, and Constantino compared DXA with six other 2C models including hydrostatic weighing, skinfold thickness, air displacement plethysmography, near infrared reactance, and three different bioelectrical impedance methods (Burns, Fu, & Constantino, 2019).

They reported hydrostatic weighing, skinfold thickness, air displacement plethysmography, and 4-electrode bioelectrical impedance analysis were closest to DXA BF% estimates; however, this study only included college-students. This is an important limitation as historically, a key drawback of the 2C models is the assumption protein, mineral, and body water are identical densities regardless of age, sex, and race. Newer 2C technologies need to ensure their BF% estimates are consistently accurate across both sexes, a wide range of ages, and many races while simultaneously prioritizing accuracy, precision, and ease of use.

The Size Stream Body Scanner is mainly used by the apparel industry but has the potential to be a 2C model that is faster than common 3C and 4C models and with reduced participant burden and greater reliability. This method uses infrared depth sensors to measure over 200 body segment circumferences and diameters in less than 30 seconds to ensure excellent garment fit but these metrics can estimate body volume and then BF% in a similar manner to air displacement plethysmography used by the BODPOD. This method might also reduce access barriers for non-clinical individuals or athletes who do not have access to college or university DXA machines. The purpose of this study was to develop a BF% estimation equation using Size Stream measures and compare that BF% estimation with other common 2C models against DXA BF% estimates.

Materials and Methods

Study Design and Participants

This cross-sectional investigation was approved by the University of Missouri Institutional Review Board (IRB #2007131) and was in accordance with the Declaration of Helsinki and its amendments. Inclusion and exclusion criteria included men and women between the ages of 18 – 65 years, no metal implants, or self-reported pregnancy. In total, 155 participants (men n = 75 and women n = 80) aged between 18 – 62 years were informed of study procedures, potential risks, and provided written informed consent.

Anthropometrics and Skinfolds

Participants reported to the laboratory having abstained from food for 4 hours, caffeine for 12 hours, alcohol for 24 hours, and exercise for 6 hours. All participants were instructed to wear minimal clothing that was tight, such as spandex. Height and weight were measured to the nearest 0.1 cm and 0.1 kg using a Seca216 stadiometer (Seca, Chino, CA) and calibrated scale (Cosmed, Concard, CA), respectively. Additionally, waist and hip circumference were measured to the nearest 0.1 cm to calculate waist:hip (WHR). Skinfold measurements were taken at the following seven sites: subscapular, tricep, midaxillary, chest, abdomen, suprailiac, and thigh using a Lange caliper (Cambridge Scientific Industries, Cambridge, MD), as previously described (Ball, Swan, & DeSimone, 2004; Ball, Altena, & Swan, 2004). Two skin fold equations were used, the Jackson-Pollock (JP7) and the DXA Criterion (DC). The JP7 equation (Jackson & Pollock, 1985) was used to estimate body density based off the seven site skinfold values and then plugged into the Siri equation for the calculation of BF% (Siri, 1956).

The newer DC equation also uses the seven site skinfold values like JP7 but does not utilize a body density conversion formula when calculating BF%, see Ball, Swan, & DeSimone, 2004 and Ball, Altena, & Swan, 2004 for details. All skinfold measurements were taken by the same technician with published intraclass correlation coefficients (ICCs) ≥ 0.98 (Ball, Swan, & DeSimone, 2004; Ball, Altena, & Swan, 2004).

Body Volume Measures

Participants also completed BF% estimations using BODPOD and Size Stream. Air displacement plethysmography was completed using the BODPOD (Cosmed, Concord, CA) as previously described (Ball & Altena, 2004). In brief, participants wore tight fitting clothes such as spandex and a swim cap and were instructed to sit still within the pod. After two consistent measures of body volume, density was determined and then plugged into the Siri equation to calculate BF%. The reliability of BODPOD BF% estimates in our laboratory are $R \geq 0.95$ (Ball & Altena, 2004). Next, participants underwent a body scan using the Size Stream (Size Stream, SS14, LLC, Cary, NC). Machine calibration was completed each day per manufactures recommendations and the body scan took less than 30 seconds for each participant who stood with their feet on the placement guides, grasping the handles, and maintaining a slight bend in the arm (Ryder & Ball, 2012).

The Size Stream collects and calculates over 200 anthropometric variables such as segment circumferences and diameters. Using Lasso (Least Absolute Shrinkage and Selection Operator) regression (Ranstam & Cook, 2018), we aimed to create the most parsimonious equation for the accurate estimation of BF% using DXA as the reference criterion. These novel prediction equations for both male and females are found in Table 1.

Table 1. Size Stream regression equations for males and females.

Male	Female
BF% = 24.77 + (-0.04*a) + (-0.21*b) + (0.73*c) + (-0.41*d) + (-0.46*e) + (-0.02*f) + (0.44*g) + (-0.88*h) + (-6.77*i)	BF% = 36.62 + (-0.01*a) + (-1.16*b) + (0.65*c) + (0.56*d) + (0.45*e) + (-0.09*f) + (0.02*g) + (0.38*h) + (-0.01*i) + (0.14*j) + (-1.32*k) + (-19.52*l)
a = neck circumference (in)	a = age (yrs)
b = right arm length	b = neck circumference (in)
c = maximal stomach circumference (in)	c = abdomen circumference (in)
d = left mid-thigh circumference (in)	d = right mid-thigh circumference (in)
e = chest diameter (in)	e = pants waist (in)
f = height (in)	f = chest diameter (in)
g = 50% waist	g = back diameter (in)
h = collar circumference (in)	h = waist circumference (in)
i = WHR (waist to hip ratio)	i = height (in)
	j = head circumference (in)
	k = cross chest arm to arm (in)
	l = WHR (waist to hip ratio)

DXA

Lastly, a total body dual-energy x-ray absorptiometry (DXA) scan was conducted (Hologic, Horizon A, APEX v. 5.6.0.5, Hologic Inc, Marlborough, MA). DXA calibration and scanning methods for our laboratory have been previously published (Baker et al., 2020); in summary, the scan took no more than three minutes for each participant who laid supine with palms against the DXA table and feet rotated inwards. Measures of total fat mass (FM) (g), % fat mass (%FM), and bone-free lean body mass (LM) (g) were obtained from the whole-body scan. The coefficient of variation percent for all body composition variables from the DXA ranges from 0.92 - 1.02% (Baker et al., 2020).

Statistical Analyses

Agreement between techniques was assessed using three methods as previously described (Dixon et al., 2018). Data were analyzed separately for males and females using IBM SPSS (v26, Armonk, New York) and alpha was set a $p < 0.05$. Values are expressed as mean ± standard deviation (SD). A one-way ANOVA with Bonferroni post-hocs were performed to detect significant differences in %BF among the five testing methods (JP7, DC, BODPOD, Size Stream, DXA). Intraclass correlation coefficients (ICC) with a two-way mixed model and absolute agreement required were calculated between the four techniques and DXA. Lastly, Bland-Altman analyses were used to compare each assessment to the DXA. Non-significant differences indicate excellent agreement and were further plotted. Bland-Altman plots were used to identify the 95% confidence interval (CI) of the mean difference, limits of agreement (LOA), variability in individual measures, coefficient of variability (%CV), constant error (CE), and total error (TE) to examine the accuracy of each equation or device compared to DXA-derived %BF estimate as previously described (Barnas & Ball, 2020).

Results

In total, 155 participants completed testing procedures but 21 participants (males n = 7, females n = 14) were excluded due to not completing at least one of the BF% estimates. For the analysis, a total of 134 participants (male n = 68; female n = 66) aged 19 – 62 years were included (Table 2). For males average BMI was in the overweight category but WHR was normal and females were normal BMI and average for WHR (Streng et al., 2018).

Table 2. Participant characteristics for the whole group and each sex – mean (SD).

Measures	**Males** n=68	**Females** n=66
Age (years)	27.7 (10.1)	28.4 (10.5)
Height (m)	1.8 (0.1)	1.6 (0.1)
Weight (kg)	83.3 (12.7)	64.3 (10.6)
BMI (kg/m^2)	26.2 (3.0)	23.6 (3.2)
WHR	0.85 (0.06)	0.75 (0.04)

SD: Standard deviation; BMI: body mass index; WHR: Waist to hip ratio

Comparison of Body Composition Assessments

The one-way ANOVA revealed significant BF% differences between all assessment tools for males (F[4, 268] = 77.715, $p \leq 0.001$) and females (F[4,260] = 56.61, $p \leq 0.001$) when compared to DXA-derived %BF (Table 3). Bonferroni post-hoc analyses revealed no significant difference between the Size Stream equation for both sexes and the female DC equation were not significantly from DXA-derived %BF. All ICC's for each measure compared to DXA for each sex were significant (all $p < 0.001$). JP7 and BODPOD had the lowest ICC's ranging from 0.625 to 0.805 for each sex. DC and Size Stream had higher ICC's, ranging from 0.848 to 0.926 for the DC and 0.866 to 0.914 for the Size Stream.

Table 3. Comparison of body composition assessments and DXA-derived %BF estimates.

Sex	Test	BF% Mean (SD)	Mean Diff. %	CV %	SEE %	Total Error %	CE ± 1.96SD %	LOA %	95% CI
Male (n=68)	DXA	18.4 (4.1)							
	DC	15.6 (4.9)	-2.8 ‡	31.6	2.2	3.5	-2.8 ± 4.5	-7.2 – 1.6	-3.4 – -2.7
	Size Stream	17.9 (2.9)	-0.5	16.0	1.7	2.4	-0.5 ± 4.7	-5.2 – 4.2	-1.1 – 0.1
	BODPOD	20.4 (7.8)	2.0 *	38.1	5.4	5.9	2.0 ± 5.6	-9.0 – 12.9	0.7 – 3.4
	JP7	12.0 (5.5)	-6.4 ‡	45.7	2.5	6.9	-6.4 ± 5.0	-1.3 – 11.5	-7.0 – -5.8
Female (n=66)	DXA	26.7 (5.5)							
	DC	26.8 (5.8)	0.1	21.5	2.9	2.9	0.0 ± 5.9	-5.9 – 5.9	-0.7 – 0.8
	Size Stream	26.9 (4.2)	0.2	15.8	2.1	2.8	0.2 ± 5.4	-5.2 – 5.6	-0.5 – 0.9
	BODPOD	29.4 (8.9)	2.7 †	30.3	8.6	6.1	2.6 ± 11.0	-8.4 – 13.6	1.2 – 4.0
	JP7	21.4 (5.8)	-5.3 ‡	27.2	3.0	6.2	-5.4 ± 5.8	-11.3 – 0.5	-6.4 – -4.6

SD = standard deviation; Diff: Difference; %CV = coefficient of variation; SEE = standard error of the estimate; CE = constant error; LOA = limits of agreement. 95% CI = 95% Confidence interval of the mean difference; DC = DXA criterion equation; JP7 = Jackson and Pollock equation (7 site). Significantly different from DXA (* $p<0.05$; † $p<0.01$; ‡ $p<0.001$).

Using the Bland Altman tests for males JP7 ($\bar{x}$= -6.420; $p < 0.001$), the DC ($\bar{x}$= -2.807; $p < 0.001$), and the BODPOD ($\bar{x}$= 2.002; $p = 0.004$) all violated the test of agreement and were not plotted. For females JP7 ($\bar{x}$= 5.377; $p < 0.001$) and the BODPOD ($\bar{x}$= -2.609; $p < 0.001$) both violated the test of agreement and were not plotted. While the equations fell within the acceptable limits, the 95% CI of the mean difference does not include a constant difference of zero suggesting there is significant systematic differences between these assessment techniques and DXA-derived %BF. Individual measurement variability for the male JP7 equation, DC equation, and BODPOD were 2.7%, 2.2%, and 5.6%, respectively. Individual measurement for the female JP7 and BODPOD were 3.0% and 5.6%, respectively.

The Size Stream demonstrated significant agreement with a nonsignificant difference of -0.525 ($p = 0.075$; see Figure 1 – top panel A and Table 3) for males and -0.193 ($p = 0.573$; see Figure 1 – bottom panel B and Table 3) for females. Additionally, the female DC equation demonstrated significant agreement with a nonsignificant difference of 0.030% ($p = 0.934$; see Figure 2 and Table 3). The data points are clustered within the acceptable LOA, in addition to the 95% CI of the mean difference, and the constant difference near zero suggesting excellent agreement between the two measurements. Individual measurement variability for the male Size Stream equation, female Size Stream equation, and female DC equation were 2.4%, 2.8%, and 3.0%, respectively.

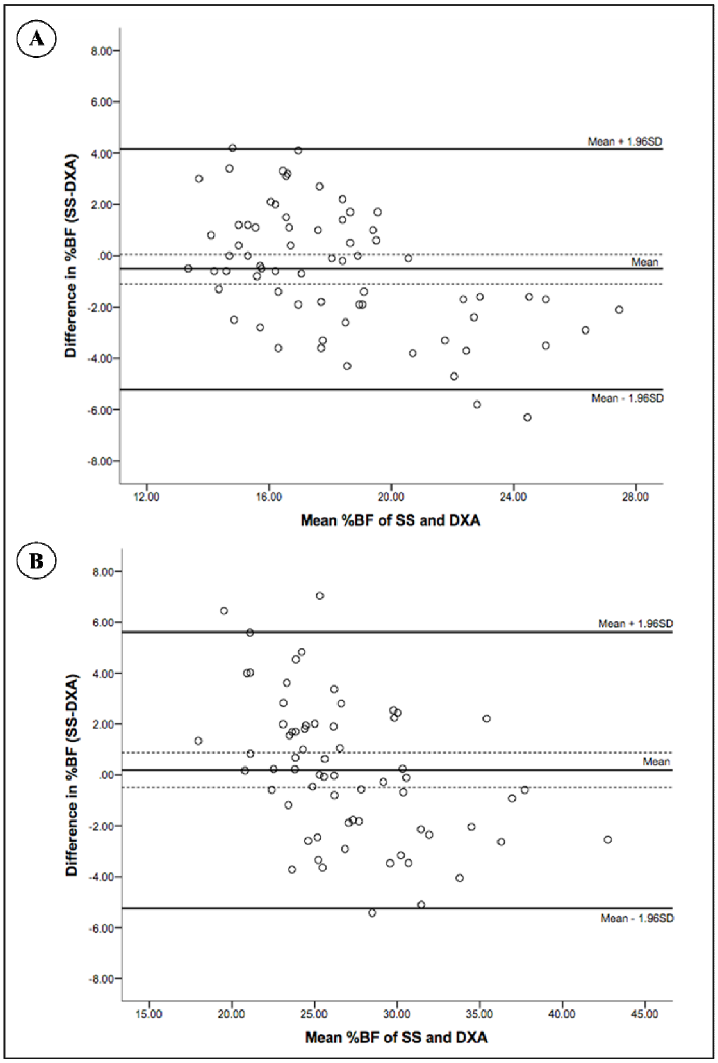

Figure 1. Difference against mean for %BF between DXA and Size Stream male equation (top panel A) and Size Stream female equation (bottom panel B). Each data point represents the difference between measured body fat percentage (DXA) and predicted body fat percentage by the sex-specific Size Stream equation. The solid lines represent limits of agreement and the mean difference for males (-0.5235 ± 2.39 %; panel A) and for females (0.193 ± 2.77 %; panel B). The dotted lines represent the 95% confidence interval of the difference.

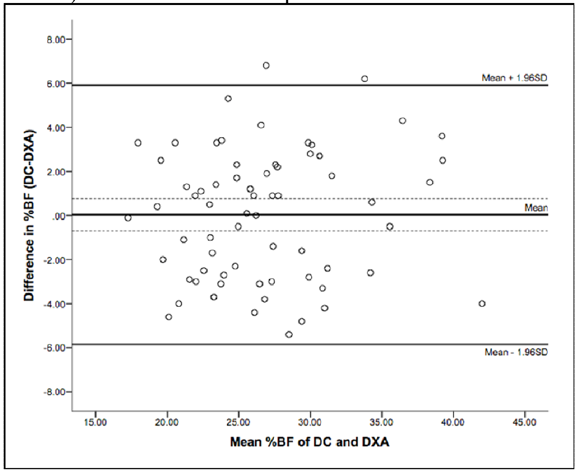

Figure 2. Difference against mean for %BF between DXA and the female DC equation. Each data point represents the difference between measured body fat percentage (DXA) and predicted body fat percentage by the female DC equation. The solid lines represent limits of agreement and the mean difference (0.03 ± 5.88%) The dotted lines represent the 95% confidence interval of the difference.

Discussion

Body composition and more specifically the estimation of BF% can be an important aspect of clinical patient care. As many consider DXA the new criterion reference and its utilization in both clinical and athletic / performance settings continues to increase, one may suggest 2C models, such as what were compared in this investigation, will continue to lose popularity. However, 2C models will remain the most popular method of assessment due to reduced time, cost, and access barriers compared to DXA and other 4C models. The purpose of this study was to first develop novel BF% estimation equations using the Size Stream and second to compare which 2C model (the newly developed Size Stream BF% equation, JP7, DC, and BODPOD) would be most accurate compared to the reference criterion DXA, thus providing evidence for its consideration as a novel 2C body composition model. The Size Stream Body Scanner proved to be the most accurate, fastest, and easiest 2C BF% estimate assessment technique compared to DXA, suggesting it may be an excellent 2C alternative.

The idea of a 2C, 3C, or 4C gold-standard body composition assessment is dependent upon historical competence and practitioner's needs moving into the future. Hydrostatic weighing was long considered the research laboratory reference standard while skinfolds and equations such as JP7 were considered standards for field testing or non-academic settings (Dempster & Aitkens, 1995; Jackson & Pollock, 1985). The practitioner's needs have always driven the creation of new and improved BF% estimate techniques. For instance, clinical and research laboratories required methods that were easier for participants and more accurate and precise leading to the transition from hydrostatic weighing to 4C models, to DXA. Field tests or testing in a non-academic setting has also undergone this transition with JP7 consistently underestimating BF% (Kuo et al., 2020). New equations such as the DC equations for males and females (Ball, Swan, & DeSimone, 2004; Ball, Altena, & Swan, 2004) were created but skinfolds still pose many challenges that new 2C models must address. Ideally, these new 2C models would have the same accuracy of the DXA but would be faster, easier, and cheaper. The Size Stream body scanner with our novel BF% prediction equation had the highest accuracy and agreement statistics with DXA for both sexes compared to the other 2C models included in this study, suggesting it would be best 2C option. Our data support findings from the literature showing this technology has great potential to be highly accurate when compared to present and past 2C (Harbin et al., 2018), 3C (Ng et al., 2019), and 4C (Tinsley et al., 2020) BF% assessment techniques.

The Size Stream also overcomes many limitations of the other 2C, 3C, and 4C techniques. For example, individuals with large body size or reduced range of motion may not fit in the BODPOD but the Size Stream is free standing and potentially more comfortable for these individuals. Furthermore, the Size Stream can accommodate individuals over 2 m tall and without width restriction but most DXA models have a scanning area that is at or under 2 meters tall and 1 m wide. Additionally, adipose tissue thickness is a limitation for many skinfold calipers, but the Size Stream uses circumferences and diameters instead. Serial body composition assessments are necessary for certain clinical and athletic populations and the radiation exposure of DXA may be of concern, but the Size Stream uses 3-dimensional optical imaging thus reducing participant risk. Additionally, access to DXA is often limited to clinical or research settings while Size Stream could be used in many sport settings, increasing athlete access. Lastly, the Size Stream is a more cost-effective option, costing less than $20,000 while DXA and BODPOD can cost well over $100,000 and $50,000, respectively. Taken together, this investigation suggests the Size Stream body scanner has the potential to be an excellent BF% estimation method when working with cohorts that do not have access to the more accurate DXA or 4C methods such as smaller schools, sports teams, or exercise gyms.

As previously noted this investigation spans multiple age ranges and includes both males and females thus increasing the generalizability compared to other age-specific studies (Burns, Fu, & Constantino, 2019). However, a key limitation of this study is the participant racial and ethnic demographics were rather homogenous and race-specific body composition assessment method bias has been noted elsewhere (Meyer et al., 2011). Future studies need to expand Size Stream testing to larger and more racially diverse cohorts to fully support it use. Additional, testing also needs to include individuals with unique body shapes and sizes such as amputees, those with severe obesity, little people, or body builders in order to better understand the potential utility of the Size Stream as a body composition assessment tool.

Conclusion

In conclusion, this study demonstrates that the Size Stream may be a suitable 2C model for BF% estimation as it closely mirrors values garnered from DXA. Additionally, the Size Stream produces these results while overcoming some 2C, 3C, and 4C model-related limitations such as patient burden, time, costs, accuracy and precision.

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Conflicts of Interest

This research was not supported by any external funding source and the authors declare they have no conflicts, financial interests, or benefits that have arisen from the applications of this research.

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