# Body composition, body mass and cardiovascular health in mid-childhood and midlife: A compositional data analysis

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**Abstract**

**Background:** We aimed to quantify associations of cardiovascular (CV) large and small artery measures with body composition and body mass (1) separately and (2) in combination in 11-12-year-old children and their parents.

**Methods:** In the population-based cross-sectional Child Health CheckPoint study (1495 children, mean 12±0.4 years, 49.3% girls; 1496 parents, mean 44.3±5.0 years, 86.7% mothers), we measured weight, height, body composition (truncal fat, non-truncal fat, FFM), and CV functional (blood pressure, pulse wave velocity, arterial elasticity) and structural (carotid intima-media thickness, retinal arteriolar/venular calibre) outcomes. Using compositional data analyses, we examined associations of body composition (expressed as log ratios) and body mass (multiplicative total) with CV measures in separate and combined models.

**Results:** Mean BMI z-score was 0.3 in children (SD 1.0, 4.5% obese) and mean BMI was 27.9 in parents (SD 6.1, 28.8% obese). In both children and adults, more adverse CV measurements were associated with higher % truncal fat, % non-truncal fat, and body mass and lower % FFM. Compared with normal-weight children, children with obesity had poorer CV measures (e.g. 1 SD faster PWV, 0.5 SDs lower arterial elasticity), with higher body mass and lower % FFM mainly accounting for these relationships. All relationships were similar, albeit larger, for parents.

**Conclusion:** Poorer CV health in both generations was associated with higher body mass, lower % FFM, and, to a lesser extent, higher % truncal and non-truncal fat. Trials could test whether weight reduction interventions with vs without fat-free mass preservation differentially improve CV functional and structural precursors.

**Impact statement**

This study reveals that poorer large and small artery health in children and parents is more strongly linked to higher body mass and lower fat-free mass than to fat mass itself. Obesity interventions focusing on weight loss with fat-free mass preservation may offer promising avenues for reducing long-term CV risk.

## INTRODUCTION

A substantial portion of cardiovascular disease (CVD) originates from childhood cardiovascular (CV) risk, with elevated childhood BMI as a major contributor.[1,2] Childhood[3,4] and adult[5,6] obesity are associated with poorer CV measures, including higher blood pressure (BP), faster pulse wave velocity (PWV), lower arterial elasticity, abnormal retinal vessels (narrower arterioles, wider venules) and greater carotid intima-media thickness (cIMT), all predictive of long-term CV outcomes.[7-9] BMI associations begin from as young as age 2-3 years.[10,11] However, despite decades of research, interventions still have marginal impacts on BMI in children who are obese,[12] with new directions hindered by limited clarity as to which BMI components drive CV risk.

Most studies examine body mass alone or only one component of body composition in relation to CV measures, or analyse body fat percentage without accounting for fat-free mass (FFM). This approach neglects their interdependence: as % fat mass increases, % FFM must fall by exactly the same amount, meaning they are perfectly collinear. Similarly, regressing body mass against CV measures without body composition may miss critical real-life relationships. However, standard regression models cannot statistically consider both in the same model. Compositional data analysis (CoDA)[13,14] overcomes these limitations by expressing body composition as log ratios, enabling simultaneous exploration of truncal fat, non-truncal fat, and FFM along with body mass in relation to CV outcomes.[15] This approach could provide clearer insights into body composition's role in CV health and thence guidance for obesity prevention and intervention strategies.

The Child Health CheckPoint study enabled us to apply CoDA in a large cross-sectional study of 11-12 year old children and their mid-life parents, examining multiple CV functional and structural measures across various body compositions. We reasoned that replicating any

associations in the parents would give confidence in the findings across more extreme BMIs than seen in our healthy child cohort, and congruence could have implications for family interventions since child and parent determinants are closely linked. Our study sought to identify which elements of body size and composition – FFM, truncal fat (TF), and non-truncal fat – are most strongly associated with adverse CV profiles. Specifically, we aimed to explore associations of CV measures (here considered as 'outcomes') with body composition and body mass (1) separately and (2) in combination.

## METHODS

### *Study Design and Participants*

The Child Health CheckPoint (CheckPoint) was a cross-sectional population-derived sub-study nested within the Longitudinal Study of Australian Children (LSAC), whose design is outlined elsewhere.[16, 17] Briefly, LSAC recruited a nationally- representative birth cohort (B cohort) of 5107 infants (aged 0-1 years) using a 2-stage clustered design and followed them up in biennial 'waves' of data collection from 2004.[16] Among them, 73.7% (n=3764) were retained to wave 6 in 2014. All wave 6 participating families were invited to consent to sharing of their contact details being shared with the CheckPoint team. 1874 children (53.3%) participated with a parent in this cross-sectional biophysical wave between February 2015 and March 2016. Supplementary file 1 describes the study procedures and ethical approvals.

### *Measures*

**Table 1** provides equipment and brief protocol on all anthropometric (height, body composition, weight) and cardiovascular (BP, PWV, cIMT, arterial elasticity and retinal vascular calibre) measures. Details of each measurement and reproducibility information have been published elsewhere.[18-21] Regarding our exposure, gold standard measures of body

composition include air (ADP) or water (WDP) displacement plethysmography and MRI, but these are not feasible for large-scale, multi-site, high-throughput field measurement. Both dual-energy X-ray absorptiometry (DXA)[22] and 4-limb segmental Bioimpedance Analysis (BIA)[23] closely approximate ADP; we used BIA because it is inexpensive, readily transportable and is easy and fast to use.

Age, sex, and family socioeconomic position (SEP) were selected as *a priori* potential confounders as they have been shown to associate with both exposures and outcomes. Puberty is a period of changes in both CV measures and body composition;[24] thus, we also considered self-reported pubertal stage/status as a confounder in children. We also included participant height because children who gain more weight tend to be taller in childhood, while shorter adults accumulate more BMI throughout their lifecourse.[25] The remaining Table 1 variables were considered in sensitivity analyses (see below).

***Statistical analysis***

All analyses were performed using R (version 4.2.1) with ggtern[26] and compositions packages[27] and a prespecified analysis plan. Children and parents were considered separately. Exploratory analyses plotted body composition in ternary diagrams, with data points colour-coded according to total body mass. Pearson's coefficient (r) described correlations between independent variables (analysis exposures). Our dependent variables (analysis outcomes) were the CV measures.

Three-part body composition (%FFM, %non-TF and %TF) was expressed as two isometric log ratios, following Dumuid et al.,[15] and using the default ilr() function from the compositions package. The expression for the set of isometric log ratios [ $IL\,R_{1FFM\,vs\,TF\wedge NTF}, IL\,R_{2TF\wedge NTF}$ ¿is as follows:

$$ILR_{1FFM\ vs\ TF \wedge NTF} = \sqrt{\frac{2}{3}} \ln \frac{FFM}{\sqrt{TF \cdot NTF}},$$

$$ILR_{2TF\ vs\ NTF} = \sqrt{\frac{1}{2}} \ln \frac{TF}{NTF}.$$

Following published CoDA procedures, total body mass was expressed as a multiplicative total (normalised sum of the log of raw kg in each component) to normalise distribution of model residuals and to allow interpretation of absolute mass effect sizes independently of body composition effect sizes in statistical models.[15]

We addressed each of our two study aims via three sets of linear regression models and used model-estimated outcome measures for a range of different plausible body composition and/or body mass combinations to describe associations. Supplementary File 2 describes Aim 1 and 2 analyses in detail. Acknowledging that the regression coefficients of body composition log ratios may not seem intuitive, we used published methods to help interpret CoDA findings.[15] All models were adjusted for age, sex, family SEP, height and (for children only) pubertal stage.

In sensitivity analyses, models were additionally adjusted for high-sensitivity C-reactive protein (hs-CRP), smoking, and the activity composition (average daily time spent in sleep, sedentary behaviour, light physical activity and moderate-to-vigorous physical activity) expressed as a set of isometric log ratios using published methods.[28]

## RESULTS

### *Sample characteristics*

Of the 1874 CheckPoint families, 1495 11-12-year-olds (mean age 12.0 years, SD 0.4, 49.3% girls) and 1496 adults (mean age 44.3 years, SD 5.0, 86.7% mothers of participating child) had valid body composition data available. sFigure 1 shows the participant flow. Participant

characteristics of the largest analytical sample (child n=1329, adult n=1424) are displayed in Table 2. SEP of the children in our sample (mean 0.25, SD 0.97) was slightly higher than that of all 5107 children enrolled in LSAC at baseline (mean 0, SD 1.0). Mean body mass (kg) was 45.4 (SD 10.3) for children and 77.0 (SD 18.2) for adults.

The long, thin vertical distribution of children's and adults' body composition (Figure 1) indicates that variation in both samples was predominantly between %FFM and two fat components, with %TF and %non-TF increasing/decreasing in almost equal proportions. There was very little horizontal variation (ie between %TF and %non-TF only). The exception was that, among the heaviest adults (shown in red), %FFM stabilised while %non-TF continued to rise at the expense of falling %TF.

In sFigure 2, we predicted body composition across the multiplicative total mass. The figures show that %non-TF is higher than %TF among children with low multiplicative total mass. However, with increasing total mass, %TF increases more rapidly than %non-TF, so they are at about the same proportions (~15%) among children with very high multiplicative total mass (>4.5, equivalent to 53 kg). Among adults, the increasing multiplicative total is associated with similar rates of increase in %non-TF and %TF until the multiplicative total is very high (>6, 106 kg), and the increase in %non-TF overtakes plateauing %TF.

***Aim 1: Associations of CV measures with body composition and body mass separately***

***Body composition:*** CV measures have been reversed where indicated so that, in all cases, a higher z-score (greater blue saturation) indicates a more favourable outcome. For **children** (sTable 1)**,** body compositions with higher %FFM and lower %TF and %non-TF were consistently associated with better CV measures (ie lower PWV, higher carotid arterial elasticity, smaller cIMT, wider retinal arteriolar and narrower venular calibre). The colour gradient in Figure 2 similarly appears to be driven by the proportion of %FFM. However (and

differently from children), at the lowest %FFM, the strongest associations appear to be among the heaviest adults (sTable 2, Figure 2 (b)) with more %non-TF than %TF.

**s**Table 3 shows estimated differences and 95% confidence intervals for all the CV measures in children and adults. Across different child body composition proportions, when FFM reduced from 90% to 55%, functional CV measures were poorer. Structural CV measures were also poorer but less markedly. Like children, the structural CV measures showed less marked, but nonetheless concerning, gradients.

***Body mass:*** Body mass (expressed as multiplicative total) was associated with all CV measures (all $p<0.05$) except retinal venular calibre in children and adults. Model parameters can be found in Supplementary Tables 4 and 5. For children (Figure 3 (a)), associations were strongest for PWV, with approximately 1.5 SD between predictions for the highest (~90 kg) and lowest (~25 kg) body mass in children. Associations were stronger among adults than children (Figure 3(b)). Similar to children, associations among adults were strongest for functional measures, with PWV being 2.5 SD higher in the heaviest (166 kg) vs lightest (42 kg) adults.

Increasing total body mass from 40 kg to 70 kg in children and 60 kg to 120 kg in adults was consistently associated with poorer systolic and diastolic BP, PWV, and arterial elasticity; differences in structural CV measures were smaller. See sTable 6 for 95% confidence intervals.

***Aim 2: Associations of CV measures with body composition and body mass combined***

sTable 7 shows that, as the BMI category rose from underweight to obesity, **children's** FFM fell from 88% to 60%, while non-TF rose to ~20%; adults' FFM fell from 74% to 49%, non-TF and TF rose from 13% to 23~27%. The combined CoDA models showed that both children's body composition and body mass were associated with more adverse CV measures

(except with retinal venular calibre), all $p<0.05$. For PWV, systolic BP and elasticity (adults only), there were interactions between body composition and body mass ($p<0.01$). Full model parameters are presented in sTables 8 and 9. The combined associations of body composition and body mass with CV measures were in the same direction among children and adults. In adults, increasingly extreme classes of obesity markedly reduced PWV, elasticity and cIMT without additionally increasing proportions of TF.

Figure 4 shows estimated CV z-scores for the average body composition and total mass of children and adults of different weight status; as results for systolic and diastolic BP were similar, only systolic BP is shown to better visualize the results. Lower body mass (smaller size of dots) together with higher %FFM (left panel) and lower %non-TF (middle panel) and %TF (right panel) were associated with better CV measures (higher z-score). Adverse associations were larger for functional than structural measures. Systolic BP was estimated to be more than 1.5 SD higher and PWV approximately 1 SD higher for body compositions and body masses of children with obesity than with normal weight.

***Sensitivity analysis***: The combined models were repeated with additional adjustments for hs-CRP, smoking and the 24-hour activity composition. Patterns of association between body composition, multiplicative mass and CV measures remained following the additional adjustment (see Supplementary sTable 10-11, sFigure 3).

## DISCUSSION

### *Principal findings*

Using CoDA, higher total body mass in conjunction with lower %FFM appeared to be the strongest drivers of adverse CV measures both in children and adults, especially for functional measures (higher systolic and diastolic BP, greater PWV, lower carotid arterial elasticity). Associations were sizeable: compared to children with normal weight, systolic BP

and PWV in children with obesity were estimated to be more than 1.5 SD and 1 SD higher respectively. In adults, effect sizes appeared larger, possibly due to their older age and the presence of more severe (classes II and III) obesity.

***Strengths and limitations***

Our study has several strengths. We appropriately used CoDA techniques[13] to empirically investigate the combined association between body composition, body mass and CV measures. The CoDA approach enabled us to include all body composition parts in the same analytical model, which is not possible with traditional regression models due to perfect multicollinearity between the parts. We included extensive CV measures within the same individuals, characterising both functional (ie BP, PWV, arterial elasticity) and structural (ie cIMT, retinal arteriolar/venular calibre) CV measures, which have each been associated with subsequent CVD in adults.[7-9] We simultaneously investigated the same associations using data from the same equipment, protocols and measurement sessions in children and adults from a single cross-generational sample, thereby minimising differences in all of the analysis, measurement, batch and confounding structures.

We acknowledge some limitations. Firstly, all measures were collected cross-sectionally, precluding causal conclusions. CoDA-analysed longitudinal data could confirm how changes in body composition and body mass drive CV health over time; it would be fascinating to see previous excellent longitudinal reports[29] re-analysed using these principles. Secondly, only 4.5% of children were classified as obese in this healthy population sample, which could limit generalizability to populations with higher rates of obesity. However, similar findings in analyses for the parents (with more prevalent and more severe obesity) support the robustness of the children's results despite the smaller numbers with high BMI. Limited data were available for adult men as most parents in the CheckPoint sample were women, who

generally have a higher body fat percentage,[30] while men have lower body fat but with a higher risk of CVD.[31] We adjusted for sex in all models and did not see an interaction effect of sex. Use of gold-standard displacement plethysmography or MRI might have enhanced the precision of our findings, which were nonetheless clear and consistent with BIA. Lastly, the self-assessed Pubertal Development Scale is considered valid and (unlike clinical assessment[32,33]) acceptable for field settings.[34] Any resulting misclassification is unlikely to have altered our findings given the scale's very small contribution to models in the children and the congruence of findings with the adults, who for obvious reasons did not complete it.[32]

***Interpretation in light of other studies***

% FFM was protective, while both % TF and % non-TF were detrimental to CV health at similar strength, with % FFM generating the strongest associations. This is consistent with the Southampton Women's Survey, in which high fat mass and low lean mass index measured by DXA were associated with higher PWV in 983 children aged 8-9 years.[35] In contrast, the Avon Longitudinal Study of Parents and Children (ALSPAC) found, in 3863 children with fat mass and lean mass measured by DXA at 9, 17 and 24 years,[29] that high cumulative exposures to lean mass (but not total fat or TF mass) were *positively* associated with the 7-year increase in PWV at 17–24 years of age, which they postulated reflected arterial adaptation to an increased lean mass from childhood. It is not clear whether ALSPAC's longitudinal and our cross-sectional findings are contradictory, as our CoDA findings are in line with the literature that higher body mass (which includes FFM) has adverse impacts on developing CV health, over and above body compositional factors.[3,4] One possibility is that greater mass (including height) increases absolute blood volume and metabolic demand, leading to arterial stiffness, loss of arterial elasticity and atherosclerosis.[36] It would be interesting to re-analyse the ALSPAC data using CoDA methods to better understand the congruence of these longitudinal and cross-sectional findings.

***Implications***

Obesity management strategies may be most beneficial to CV health if they focus on reducing weight while also building relative FFM at the expense of other components of body fat. A combination of time-restricted eating with interval exercise (well suited to children's natural patterns of play and sport) appears to be a promising and sustainable free-living way to both reduce total body mass and increase FFM for CV benefit.[37, 38] Trials combining this approach in overweight/obese adults already show promise,[37, 38] with further adult (but not to our knowledge childhood) trials under way.[39] These avoid the outcomes of most weight loss programs that tend to reduce FFM (specifically skeletal muscle mass[37]), which, based on our findings, could be counterproductive to health gain.

Our models suggest multiple paths to improve CV health for any given CV phenotype. For instance, a meta-analysis has indicated that a 1 SD increase in PWV is associated with a 47% (95% CI: 1.31 to 1.64) higher risk of CV events in adults[3] and a 0.2 SD reduction in PWV could lower this risk by 10%. In a hypothetical 11-12-year-old child with average body composition and mass, a 0.2 SD PWV reduction might be achieved by either reducing total body weight by 5.6 kg (e.g. could be through smaller food portions and higher protein intake) or by maintaining the same body mass while increasing %FFM by 5.5 and reducing %non-TF by 3.4 and %TF by 2.1 (e.g. could be through resistance training programs).

Our study supported the analysis of three-part body composition (truncal, non-TF and FFM) and body mass with CV measures. Techniques such as DXA, MRI, and CT can compartmentalize body composition into different parts (i.e., separate truncal into visceral and subcutaneous fat), which have been studied using CoDA for different research questions in adults.[40-42] Studies with children using these measures may in time refine conclusions.

## CONCLUSION

In two generations, we found that body compositions characterized by high %truncal and %non-truncal fat and high absolute body mass were consistently associated with poorer CV health and higher %fat-free mass with better CV health. Associations with both structural pre-clinical and functional markers of CV health were already evident in 11–12-year-old children. In obesity intervention management programs, reducing weight while preserving fat-free mass may benefit CV health most.

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Research Electronic Data Capture (REDCap) tools were used in this study. More information about this software can be found at: www.project-redcap.org. We thank the LSAC and CheckPoint study participants, staff and students for their contributions.

## Authors' contributions

MW conceived and led the CheckPoint study with the CheckPoint team and was LSAC's Health Design Leader. ML and KL designed the study and wrote the main paper. DD and ML performed data analysis. KL, JK, SR, MC, LB designed and collected data. DD, MW, TO, DB and KL oversaw all aspects of the study and the manuscript preparation. MJ, SE, YW, SR, MC, LB, TD, JK, DB and MW provided expert advice and critical review of this manuscript. All authors critically reviewed the manuscripts and had final approval of the submitted and published version of this paper.

## Competing Interests

The authors declare no potential conflicts of interest, including no specific financial interests relevant to the subject of this manuscript.

## Data Availability Statement

Data described in the manuscript, code book, and analytic code will be available upon request pending application and approval of a data-sharing agreement.

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## Figure legends

**Figure 1.** Body composition (%) ternary plots coloured by multiplicative total body mass. Black dot indicates compositional centre of samples

The dot and dash lines indicated the means of body composition %. In children, the means of truncal fat, non-truncal fat, and fat-free mass were 7.7, 12.5 and 79.8%; in adults, the corresponding means were 7.7, 12.5 and 79.8%. There was very little horizontal variation (i.e., between %truncal fat and %non-truncal fat only). The lowest total body mass (blue) was at body compositions with lowest %truncal fat and %non-truncal fat and highest %fat-free mass. Highest total body mass (red) was at body compositions with lowest %fat-free mass and highest %truncal and %non-truncal fat.

**Figure 2.** Associations between body composition and cardiovascular health measures

Abbreviations: FFM, fat-free mass; TF, TF; NTF, non-TF; PWV, pulse wave velocity; cIMT, carotid intima-media thickness.

All models adjusted for age, sex, family socioeconomic position, height and puberty (child only). A higher z-score (blue) represents a more favourable CV measure (lower blood pressure, lower pulse wave velocity, higher elasticity, smaller carotid intima media thickness, higher retinal arteriolar calibre and lower retinal venular calibre).

Body compositions with higher %fat-free mass and lower %truncal fat and %non-truncal were consistently associated with better CV measures (ie, lower PWV, higher systolic and diastolic blood pressure, higher carotid arterial elasticity, thinner cIMT, wider retinal arteriolar and smaller venular calibre). The color gradient appears strongly driven by the proportion of %fat-free mass, as seen by the horizontal color transition (parallel to the %fat-free mass grid lines). The relative influences of %truncal and %non-truncal fat appear similar, with the bluest saturation at the lowest %truncal fat.

**Figure 3.** Associations between body mass and cardiovascular health measures

All models adjusted for age, sex, family socioeconomic position, height and puberty (child only). A higher z-score represents a more favourable CV measure (lower blood pressure, smaller carotid intima media thickness, higher elasticity, lower pulse wave velocity, higher retinal arteriolar calibre and lower retinal venular calibre). The multiplicative total is the normalized sum of the logarithms of body composition parts (in kg), whereas the sum total is the sum of body composition parts (in kg).

For all CV outcomes, higher body mass was associated with poorer CV measures. The associations were strongest for PWV in both children (1) and adults (2).

**Figure 4.** The combined associations of body composition and body mass with cardiovascular health measures

Figure 4 shows estimated CV z-scores for the average body composition and total mass of children and adults of different weight status. Three panels represent %FFM (left), %non-TF (middle), and %TF (right), respectively, and the x-axis indicates the percentage of each body composition component in three body composition panels. The y-axis indicates the estimated CV z-scores for different weight statuses. The size of the dots represents body mass in kg.

All models adjusted for age, sex, family socioeconomic position, height and puberty (child only). FFM=fat-free mass, NTF=non-TF, TF=TF, OB=obesity, OW=overweight, NW=normal weight, UW=underweight. z-scores for systolic blood pressure, carotid intima-media thickness, pulse wave velocity and retinal venular calibre reversed so that an increase always represents a favourable difference.