Pediatric RESEARCH

www.nature.com/pr

CLINICAL RESEARCH ARTICLE

A hospital-based cohort study of gender and gestational age-specific body fat percentage at birth

Tracey Leigh Lutz[1,2], Alice Elizabeth Burton[1], Jon Anthony Hyett[1,2], Kevin McGeechan[2] and Adrienne Gordon[1,2]

BACKGROUND: Birthweight is the most commonly used proxy marker but does not adequately define true nutritional status. Modalities like DXA (dual energy x-ray absorptiometry) and TOtal Body Electric Conductivity (TOBEC) have been validated to assess body composition but their accuracy in neonates has not been established. The PEAPOD (COSMED, Rome Italy) has been validated as an accurate tool for measuring percentage body fat (%BF) in newborns. The study aim was to determine the gender-specific %BF percentiles at different gestations (35–41 weeks) for a healthy population of newborn infants. A secondary aim was to determine whether there is any relationship between %BF and neonatal condition at birth (cord gas measurement).
METHODS: %BF was measured using air displacement plethysmography (PEAPOD) within 6 h of birth.
RESULTS: There is an increase in the mean %BF with increasing gestation for female and males from 36 weeks' gestation in the 7667 infants who underwent assessment. Females have a higher %BF than their male equivalents. There was no correlation between %BF and cord pH.
CONCLUSION: Gender and gestation are both important in determining the quantiles and mean %BF at birth. There was no correlation between low cord pH and %BF.

Pediatric Research (2021) 89:231–237; https://doi.org/10.1038/s41390-020-0879-5

IMPACT:

- Measuring the percentage body fat (PEAPOD) at birth is a useful marker of an infant's nutritional status.
- This is the largest hospital-based cohort of gestational age and gender-specific %BF in healthy newborns.
- The normative graphs from this study will help to accurately determine high-risk infants with low %BF so they can be monitored appropriately.

INTRODUCTION

Infant body composition is an important marker of fetal growth and nutritional status at birth. The fetus depends on placental supply of all nutrients, switching to oral nutrition as a newborn. While oral nutrition is being established, fat laid down in the third trimester provides an alternative energy source (ketones) and substrate for gluconeogenesis (glycerol). Measuring body composition at birth can help to identify infants with limited nutritional reserve who are at increased risk of short-term morbidity such as hypoglycaemia and of longer term metabolic and cardiovascular sequelae.[1,2]

Techniques for calculating body composition include dual energy x-ray absorptiometry (DXA), TOtal Body Electric Conductivity (TOBEC) and bioelectrical impedance; however, there are safety and practical limitations in infants and their accuracy in neonates has not been established.[3,4]

The PEAPOD device (COSMED, Rome, Italy) utilises air displacement plethysmography (ADP) to calculate a two-compartment model of body composition: fat mass (FM), fat-free mass (FFM) and percentage body fat (%BF) in infants from 1 to 8 kg. The system's margin of error for %BF is reported as 6–8%, with accuracy potentially affected by lower fat volumes, environmental factors and variable FFM density.[5] Notwithstanding these limitations, the system is safe, quick and non-invasive that is acceptable to parents[6–8] and can be integrated into routine clinical practice.

Carberry et al.[1] measured %BF in 518 infants within 48 h of birth. They concluded that %BF better identified neonates at risk of acute morbidity than birthweight percentiles. This finding led to a practice change at our institution, mandating blood glucose monitoring in all babies with low %BF (1 SD below the mean) even in the setting of appropriate for gestational age (AGA) birthweight.[9]

Published reference ranges for %BF by ADP are limited by samples of small and non-diverse samples, with PEAPOD typically performed around 48 h, so not applicable for risk assessment.[10,11] We sought to improve identification of infants with poor nutritional status by calculating gestation and gender-specific ranges for %BF at birth with particular focus on a large sample size and a diverse population. This would create a population standard of body composition for infants that are well enough to undergo PEAPOD assessment and facilitate interpretation of infant body composition data in various research and clinical applications.

Noting the association between low %BF and neonatal morbidity, we questioned whether infants with low %BF might have reduced tolerance for the stress of labour. Arterial umbilical cord blood is a marker of perinatal asphyxia and low pH,

[1]Women's and Babies, Royal Prince Alfred Hospital, Missenden Road, Camperdown, Sydney, NSW 2050, Australia and [2]University of Sydney, Sydney, NSW 2000, Australia
Correspondence: Tracey Leigh Lutz (tracey.lutz@health.nsw.gov.au)

Received: 4 December 2019 Revised: 5 March 2020 Accepted: 13 March 2020
Published online: 14 April 2020

particularly below 7.1, is associated with serious neonatal adverse outcomes.[12] A systematic review and meta-analysis demonstrated that low cord pH increased neonatal mortality and morbidity and cerebral palsy in children.[13] The relationship between %BF and arterial umbilical cord blood pH has not been studied and we sought to evaluate this relationship in our research.

The aims of this study were to: (1) determine the gender-specific %BF percentiles soon after birth for a large hospital-based cohort of healthy babies at different gestations (35–41 weeks); (2) ascertain whether %BF is associated with neonatal condition at birth measured by arterial cord gases.

METHODS

Study setting and participants

Royal Prince Alfred Hospital, a tertiary teaching hospital in Sydney, delivers approximately 5500 babies per year. All healthy babies born between 28 January 2014 and 9 August 2016 between 35 + 0 and 41 + 6 weeks' gestation were eligible for inclusion.

As this was an analysis of a clinical assessment that covers all newborns other than those too unwell to be measured in the PEAPOD, we had minimal exclusion criteria. The exclusion criteria included respiratory distress, major congenital anomalies or any babies who were routinely admitted to nursery (<2200 g).

Data to address aim 1 were collected prospectively as part of the Neonatal Early Assessment Program (NEAP) at our institution (study cohort 1). Access to medical records for analysis of this clinical dataset was prospectively approved by the Sydney Local Health District Ethics Committee (approved March 2016).

In addition to this large clinical dataset, a smaller prospective cross-sectional analysis of neonatal body composition was performed to address aim 2 between 4 July and 29 October 2016 (study cohort 2). This prospective cohort evaluated the relationship between neonatal %BF and umbilical cord pH, and included all live-born infants between 35 + 0 and 41 + 6 weeks' gestation who were well enough to undergo PEAPOD within 48 h of life. Pregnancies known to be affected by congenital abnormality were excluded from the study. Parents of eligible infants gave written consent. Ethics approval was obtained from the same Ethics Committee (Protocol No. X15-0315). Arterial cord blood was collected in a heparinised syringe at the time of delivery from a clamped cord within 30 min of birth.

Infant data

The NEAP (which includes detailed newborn examination, pulse oximetry screening, anthropometrics (length, weight and head circumference) and %BF assessment) was introduced as standard clinical practice for all healthy babies >35 + 0 weeks' gestation in January 2014.[14] This assessment aims to be completed within the first 6 h of life. The FFM, FM and %BF were assessed by ADP using the PEAPOD (COSMED, Rome, Italy). The %BF was computed by software integral to the PEAPOD system based on a two-compartment model of fat and fat-free compartments.

Infant length was measured using the Easy-Glide Bearing Infantometer (Perspective Enterprises, Portage, MI, USA), which is the gold standard in length measurement.[15] The PEAPOD digital scales were used to measure the weight to within 0.1 g (infants who did not have PEAPOD assessment were weighed by standard scales). The midwife measured head circumference at the time of the neonatal examination.

Maternal data

Maternal data collected included age, diabetes (gestational (defined by Australasian Diabetes in Pregnancy Society Guidelines[16]), type 1 or type 2), any smoking (self-reported) during pregnancy, pre-pregnancy weight, pre-pregnancy body mass index (BMI), mode of delivery (vaginal, assisted vaginal (forceps or vacuum), elective caesarean (no labour), emergency caesarean (intrapartum or acute emergency), and parity (nulliparous or parous).

The self-reported maternal country of birth was used as a proxy marker of ethnicity. Country of birth was categorised into region of birth using geographic regions defined by the United Nations' M49 Standard (Australia/New Zealand (Aus/NZ), South Asia, South East Asia, East Asia, Europe, West Asia (Middle East), Africa and Other[17]).

Data collection

Maternal and infant data, including umbilical cord blood gas results, were extracted from the electronic medical records and linked using medical record numbers. Body composition data were exported from the PEAPOD machine and linked by medical record numbers. Data were then de-identified for analysis.

Statistical analysis

Characteristics of mother−infant pairs who did and did not undergo PEAPOD assessment were compared using Student's *t* test or Mann−Whitney *U* test for normally distributed or non-parametric continuous data and chi-square test for categorical data (significance cut-off $p < 0.05$). Infants were grouped by completed weeks of gestation (35, 36, 37, 38, 39, 40 and 41 weeks) and gender. Statistical analysis was performed using SAS Version 9.4 for Windows (SAS Institute Inc., Cary, NC, USA). Quantile regression, a technique we have previously used for growth curves,[18] was employed to construct centile curves for %BF for each gender by gestation. Regressions were fitted to polynomials of order 4, as validated previously. Resulting centile curves were checked against raw centiles for additional validation.

A sensitivity analysis was performed by removal of outliers using Tukey's method (https://www.oxfordreference.com/view/10.1093/oi/authority.20110803110053894) and comparison with the original centile curves.

One-way ANOVA with post-hoc Tukey tests were performed to assess for differences in mean %BF, FM and FFM by maternal region of birth. Two-way ANOVA was performed to assess for interaction between infant sex and maternal region of birth while ANCOVA testing was performed to adjust for length.

A chi-square test and Fisher's exact test were performed to evaluate the association between low %BF and pH < 7.1

RESULTS

There were 12,093 live-births between 35 + 0 and 41 + 6 weeks' gestation (inclusive) in study cohort 1. A total of 824 babies (6.8%) were ineligible as they were admitted to the newborn care unit (Fig. 1). In all, 7667 of 11,268 eligible infants (68%) had a %BF assessment using the PEAPOD. There were 28 sets of twins in the 7667 infants. Given the small number of twins and minimal impact on overall data analysis, twins remained in the dataset. Of the 1585 infants live-born between 35 + 0 and 41 + 6 completed weeks' gestation in study cohort 2, 1219 had PEAPOD measurements (77%). Reasons for non-assessment for both cohorts included: parental refusal, inability of the staff to accompany baby from theatre to the delivery ward for assessment and admission to newborn care unit.

Baseline maternal and infant characteristics of both cohorts are summarised in Table 1. The mean maternal age, booking weight and BMI of both study cohorts were very similar to those of our hospital's general maternity population. Pre-pregnancy obesity was not an exclusion criterion. Similarly, the distribution and spread of data for infant sex, median gestational age and mean birthweight in the two cohorts accorded with the population characteristics.

Compared to infants who underwent PEAPOD, those that missed PEAPOD had similar birthweight and head circumference, and were slightly longer (Table 1). They were born to mothers who

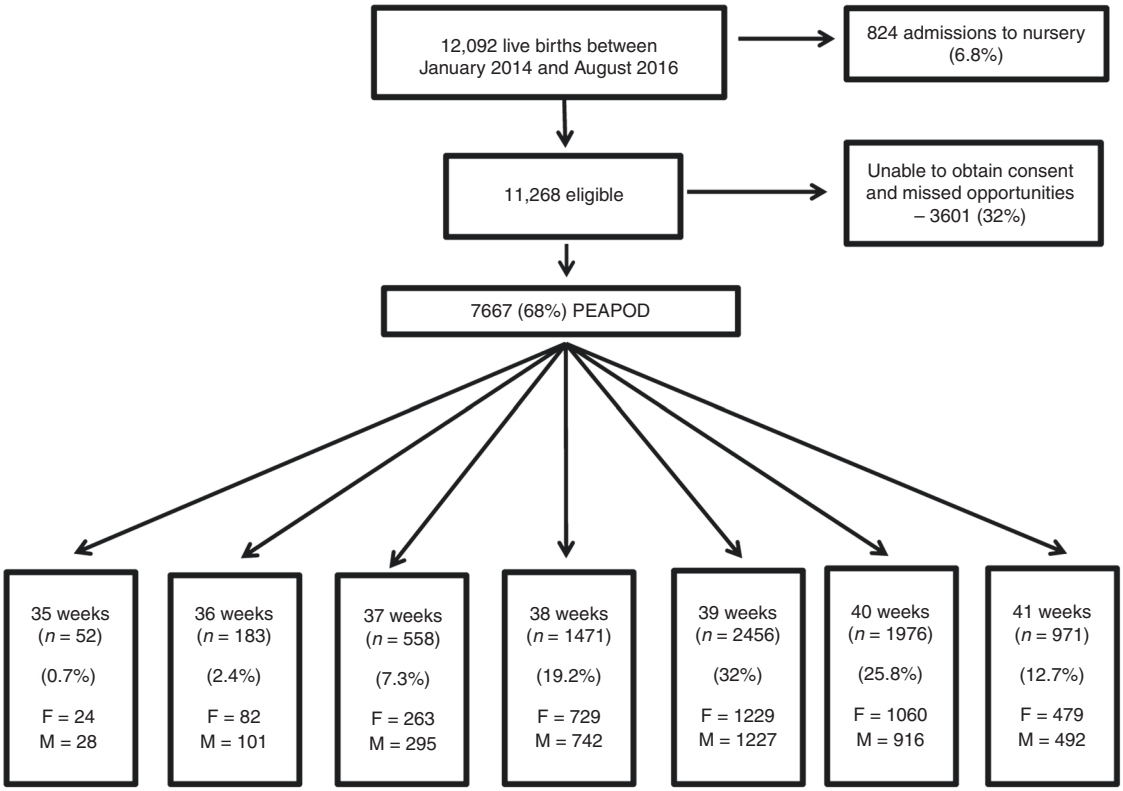

Fig. 1 Methods: The number of patients included in study. Methods—Flow chart (cohort 1).

Table 1. Baseline characteristics of the study cohorts and overall birth cohort.

Variable	Study cohort 1 $n = 7667$	Total population for study cohort 1 $n = 12{,}093$	Study cohort 2 $n = 1219$	Total population for study cohort 2 $n = 1585$
Mean maternal age (years)	32.3 (SD 4.9)	32.5 (SD 4.9)	32.4 (SD 4.7)	32.6 (SD 4.7)
Median maternal pre-pregnancy weight (kg)	60 (range 36–170)	60 (range 35–187)	60 (range 40–167)	60 (range 40–167)
Mean maternal weight at first antenatal appointment (kg)	68.7 (SD 15.7)	68.5 (SD 15.5)	69.7 (SD 17.1)	69.5 (SD 16.5)
Median maternal pre-pregnancy BMI (kg/m^2)	22.5 (range 14.8–66.7)	22.5 (range 14.8–66.7)	22.6 (range 14.5–57)	22.6 (range 14.5–57)
Diabetes in pregnancy	1769 (23.1%)	2738 (22.6%)	256 (21%)	323 (20.4%)
Smoking in pregnancy	238 (3.1%)	382 (3.2%)	26 (2.1%)	34 (2.1%)
Parity				
Nulliparous	4246 (55.4%)	6629 (54.8%)	680 (55.8%)	887 (56%)
Parous	3421 (44.6%)	5433 (44.9%)	539 (44.2%)	698 (44%)
Mode of delivery				
Elective caesarean	822 (10.7%)	1867 (15.4%)	216 (17.7%)	272 (17.2%)
Emergency caesarean	610 (8%)	1838 (15.2%)	147 (12.1%)	225 (14.2%)
Normal vaginal birth	4974 (64.9%)	6495 (53.7%)	685 (56.2%)	869 (53.6%)
Assisted vaginal birth	1244 (16.2%)	1852 (15%)	168 (13.8%)	216 (13.6%)
Breech vaginal birth	16 (0.2%)	35 (0.2%)	3 (0.3%)	3 (0.2%)
Infant sex	Male: 3809 (49.7%) Female: 3858	Male: 6173 (51%) Female: 5915	Male: 610 (50%) Female: 609	Male: 800 (50.5%) Female: 785
Median gestational age at delivery, (weeks)	39.5 (range 35–41.9)	39.4 (range 35–41.9)	39.4 (range 35.1–41.9)	39.4 (range 35–41.9)
Mean infant birthweight (g)	3346 (SD 465)	3347 (SD 484)	3364 (SD 475)	3355 (SD 491)
Mean infant length (cm)	49.6 (SD 2.3)	49.6 (SD 2.3)	–	–
Mean infant head circumference (cm)	34.6 (5.4)	34.6 (SD 5.7)	–	–

g grams, *kg* kilograms, *BMI* body mass index, *m* metre, *cm* centimetre, *SD* standard deviation.

were slightly older and heavier, at a slightly earlier gestational age, and were more likely to be delivered by emergency caesarean. There were differences in the maternal regions of birth.

Gestation-specific body fat percentiles

There is an increase in the mean %BF with increasing gestations for both female and male infants from 36 + 0 weeks' gestation (Figs. 2 and 3). The mean %BF at 35 + 0 weeks' gestation was higher than expected for both females and males likely due to the very small numbers of babies secondary to the majority of infants at this gestation being admitted to the nursery. The 35-week data have therefore not been included in the percentiles. Females have a higher %BF than their male equivalents at all other gestations (36−41 weeks).

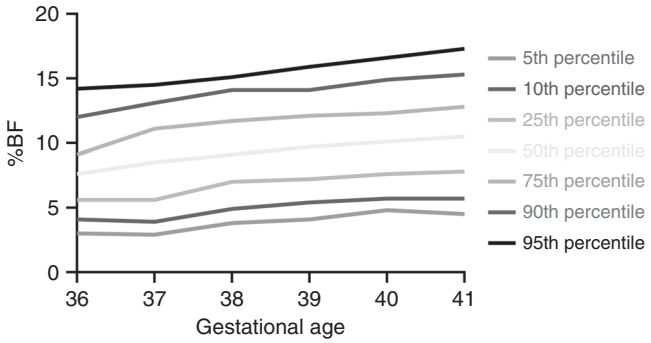

Fig. 2 Gestational-specific %BF for males.

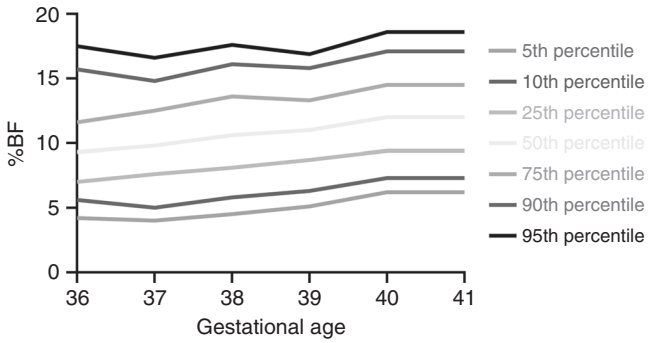

Fig. 3 Gestational-specific %BF for females.

Ethnicity

For analysis of ethnicity, infants born to mothers from the categories 'Middle East', 'Africa' and 'Other' were excluded due to small numbers and the heterogeneity of these regions, leaving 7131 infants. Results are presented in Table 2.

There were significant differences between maternal regions of birth for infant %BF, FM and FFM. Mean %BF was significantly lower for infants born to women from South Asia (9.4 ± 3.8, $p < 0.001$) than for those from South East Asia (10.1 ± 4, $p < 0.001$) and East Asia (10.1 ± 3.7, $p < 0.001$), who in turn had lower mean %BF than those from Aus/NZ (11.0 ± 4, $p < 0.001$) and Europe (10.9 ± 3.6, $p < 0.001$; Table 2.). These differences largely persisted after adjusting for length. There was no interaction between ethnicity and infant gender for %BF.

Both FM and FFM were lowest in infants born to women from South Asia, and highest in infants born to women from Aus/NZ and Europe, including after adjustment for length. Infants born to women from South East Asia and East Asia had intermediate levels of FM and FFM, as summarised in Table 2.

Body fat and neonatal condition at birth

There were only 31/918 infants who had an arterial cord gas pH < 7.1. Due to the small numbers we were unable to perform any meaningful analysis about condition at birth and %BF. There were no babies who had both low %BF and arterial cord pH < 7.1 (Fisher's exact test $p = 0.394$) (Tables 3 and 4).

DISCUSSION

This hospital-based cohort study of 7667 mother–infant pairs represents the largest cohort to date of prospectively collected early %BF in newborns and has generated gender- and gestation-specific standards. The data are representative of other tertiary Australian maternity services with a diverse population and therefore would be generalisable to other similar settings.

The distribution of %BF in our population is consistent with prior series published at our[1] and other institutions. In the Newborn Body Composition Study of the INTERGROWTH-21st Project, normative %BF data were generated from a sample of 247 low-risk mother−infant pairs with normal antenatal ultrasound growth.[11] The %BF 50th centiles for males and females at 40 weeks of gestation were, respectively, 10% and 11.4% in the INTERGROWTH-21st cohort, very similar to the values of 10.1% and 12% in our sample. Gestation- and gender-specific centiles from a low-risk Irish population were also similar.[10] Our considerably larger sample size increases the precision of our upper and lower extremes (i.e. the 10th and 90th percentiles) and has allowed us to create centiles specific to each gestational week. Other series that have reported mean %BF by gender only (i.e. not by gestation)

Table 2. Body composition by maternal region of birth.

	%BF		FM (g)		FFM (g)	
	Crude	Adjusted[1]	Crude	Adjusted[1]	Crude	Adjusted[1]
Aus/NZ	11.0 (4)[a]	10.9 (10.7–11)[a]	384 (173)[a]	377 (372–382)[a]	3028 (364)[a]	3002 (2994–3010)[a]
South Asia	9.4 (3.8)[b]	9.7 (9.5–10)[b]	302 (150)[b]	323 (313–334)[b]	2826 (325)[b]	2893 (2875–2912)[b]
South East Asia	10.1 (4)[c]	10.5 (10.2–10.8)[a]	331 (155)[c]	357 (346–368)*	2867 (331)[b]	2953 (2934–2971)[c]
East Asia	10.1 (3.7)[c]	10.1 (9.9–10.3)[b]	339 (154)[c]	342 (334–350)[b]	2944 (319)[c]	2954 (2940–2967)[c]
Europe	10.9 (3.6)[a]	10.7 (10.5–11)[a]	380 (157)[a]	368 (358–379)[a]	3029 (355)[a]	2991 (2974–3008)[a]

Crude data presented as mean (standard deviation (crude) or 95% confidence interval (adjusted)).
Within each column, each superscript letter denotes a region of maternal birth where that body composition parameter does not significantly differ from each other at the $p < 0.05$ level.
%BF percentage body fat, *FM* fat mass, *g* grams, *FFM* fat-free mass.
*Adjusted FM for South East Asia no different to East Asia and Europe.
[1]Adjusted for length.

Table 3. Sex- and gestation-dependent percentage body fat means and percentiles (study cohort 1).

Gender	Gest (weeks)	*N*	Mean % BF	SD	5th pctl	10th pctl	25th pctl	50th pctl	75th pctl	90th pctl	95th pctl
Female	36	82	9.63	4.02	4.2	5.6	7.0	9.3	11.6	15.7	17.5
	37	263	10.09	3.86	4	5	7.6	9.8	12.5	14.8	16.6
	38	729	10.86	4.01	4.5	5.8	8.1	10.6	13.6	16.1	17.6
	39	1229	11.06	3.62	5.1	6.3	8.7	11.0	13.3	15.8	16.9
	40	1060	12.07	3.98	6.2	7.3	9.4	12.0	14.5	17.1	18.6
	41	479	12.46	3.94	5.7	7.4	9.9	12.5	14.9	17.5	19.0
Male	36	101	7.77	3.25	3.0	4.1	5.6	7.6	9.1	12.0	14.2
	37	295	8.66	4.56	2.9	3.9	5.6	8.5	11.1	13.1	14.5
	38	742	9.33	3.51	3.8	4.9	7.0	9.1	11.7	14.1	15.1
	39	1227	9.74	3.52	4.1	5.4	7.2	9.7	12.1	14.1	15.9
	40	916	10.22	3.80	4.8	5.7	7.6	10.1	12.3	14.9	16.6
	41	492	10.52	3.99	4.5	5.7	7.8	10.5	12.8	15.3	17.3

Gest gestational age, *N* number, *SD* standard deviation, *Pctl* percentile, *%BF* percentage body fat.

Table 4. Sex- and gestation-dependent percentage body fat means and percentiles (study cohort 2, $n = 1219$).

Gender	Gest (weeks)	*N*	Mean % BF	SD	5th pctl	10th pctl	25th pctl	50th pctl	75th pctl	90th pctl	95th pctl
Female	36	23	9.29	2.7	4.5	5.2	7.5	9.3	10.9	13.6	14.9
	37	48	10.47	4.38	3.7	5.1	7.6	10.3	12.2	17.2	19.8
	38	117	10.36	3.73	4.1	5.1	7.8	10.3	13	15.1	16.4
	39	200	11.03	3.69	5.2	5.8	8.7	10.9	13.3	15.8	18.6
	40	144	11.9	3.58	5.8	7.3	9	12.2	14.3	17	18.3
	41	70	12.2	3.48	5.2	7.5	10	12.6	15	16.3	17.4
Male	36	21	8.42	2.89	3.3	4.5	6.4	8.1	10.6	12.6	14
	37	50	7.8	3.85	3.1	3.3	4.7	6.8	11.2	14.3	15.4
	38	122	9.59	3.85	3.1	4.6	6.9	9.4	12.2	14.8	16.8
	39	189	9.7	3.72	4	4.9	7.3	9.4	11.9	14.7	16.8
	40	144	9.16	3.65	3.5	4.9	6.1	9.2	11.5	13.5	15.9
	41	78	10.34	3.73	4.7	5.9	7.4	10.1	12.6	15.9	17

Gest gestational age, *N* number, *SD* standard deviation, *Pctl* percentile, *%BF* percentage body fat.

show some difference to our mean value[7,19,20], which may reflect ethnic and nutritional differences, as well as variation in the timing of body composition assessment.

We recognise that the timing of PEAPOD assessment in this cohort (within 6 h if possible) is different to the majority of other studies.[7,11] The main rationale for this is the %BF measurements are used as a clinical tool in our setting (not restricted to research) to identify babies at risk of hypoglycaemia. Shaw et al.[9] demonstrated that 8.5% of infants >5th percentile (AGA) plotted on population-based charts (gold standard in paediatrics) with low %BF had hypoglycaemia. Identifying low %BF on early PEAPOD therefore ensures close BSL monitoring in babies that would otherwise not have been monitored and have been at risk of missed hypoglycaemia/neonatal morbidity.

A common feature of all the previous published data is recruitment from a healthy population. In previous studies this has been by design. Our inclusion criteria were intentionally broad to adequately represent our general population but nonetheless premature and low birthweight infants were under-represented. Villar et al.[11] noted lower %BF in their preterm babies compared with the term equivalents ($n = 91$). When these preterm infants reach 'term corrected', they had a higher %BF than term infants due to an increased accumulation of fat.

Clinical audits at our institution have identified several barriers to obtaining PEAPOD measurements on all infants, including immediate admission to the Neonatal Intensive or Special Care Unit ('Nursery'), birth in Operating Theatre and device non-function. Between infants who did and did not undergo PEAPOD, birthweight was similar and the maternal age and weight differences were not likely clinically significant. However, the higher proportion of births by emergency caesarean in infants who missed PEAPOD may have been associated with under-nourishment. This along with exclusion of infants admitted to the Nursery may have skewed the distribution of %BF in the study sample towards higher values.

We found evidence of ethnic variation (defined by maternal region of birth) in body composition at birth. Infants of Australian/NZ and European background had the highest total mass (birthweight) and also the highest absolute and relative FM, including after adjustment for length. By contrast, infants of South Asian background had the lowest total mass, and also the lowest absolute and relative FM. These findings are consistent with data on the high prevalence of SGA among South Asians and may contribute to understanding the increased risk of stillbirth for South Asian women birthing in Australia.[21,22] For example, lower fetal fat stores might lead to poorer tolerance of ante- or

intrapartum stress. Alternatively, reduced adiposity may reflect common socioeconomic, nutritional and environmental risk factors with growth restriction.

Our findings differ to those of Alexander et al.[23] in their recent study of 440 term NZ infants. They reported that infants of 'Asian+' background had the highest %BF (mainly due to lower FFM). They concluded that the so-called 'thin-fat' phenotype (low lean mass and high adiposity) is apparent at birth in NZ-born Asian infants. This phenotype, recognised in South Asian adults and children, has also been described in infants of South Asian descent.[24–26] Instead, we found that infants born to South Asian mothers had low adiposity and again we consider this consistent with the high prevalence of low birthweight in Asia and specifically South Asia.[27] Our different findings may be accounted for our ability to distinguish between different Asian regions while it is possible that Asian background women in our sample are more representative of Asian resident women.

Alexander et al.[23] also reported that FM was constant across ethnic groups whereas our large sample size allowed us to identify small differences. The clinical importance of these differences remains to be clarified. Defining ethnicity is problematic, particularly in the multicultural Australian setting. We have used maternal region of birth as a proxy for ethnicity, and have not accounted for factors such as paternal ethnicity, diet and duration of Australian residency (nor have other PEAPOD studies reporting on ethnicity[23,28]).

Fetal growth and body composition have also been linked with risk of metabolic and cardiovascular disease in later life.[1] There appears to be a difference in the deposition of fat and fat-free mass in late gestation. While FFM accretion is proposed to be stable and genetically determined, fat accretion appears to be more variable.[2] Identifying factors that are associated with %BF can therefore contribute to understanding of fetal growth patterns and antenatal screening for aberrant growth.

For this reason, we intentionally included babies born to women with GDM or pre-existing DM. Because the prevalence of GDM/pre-existing DM is so high in our population, including these patients is essential especially as the quantiles are used to determine which babies are at risk of hypoglycaemia. Also, Au et al.[29] showed that in 67/599 babies born to mothers with well-controlled GDM, neonatal %BF did not differ from non-diabetic pregnancies.

Also, we did not adjust for caesarean section as half were elective with minimal intravenous fluids given prior to surgery.

Although we set out to identify whether there was a relationship between %BF and cord gases, unfortunately we were unable to assess this relationship as there were no infants who had low %BF who had a pH < 7.1. As arterial pH < 7.1 reflects condition at birth, many of these infants may have been unwell and admitted directly to the nursery and therefore did not have a %BF assessment.

The major strength of our cohort is that it represents the largest series of near term and term healthy infants with planned transfer to the postnatal ward after birth. These infants are around 94% of births and therefore the %BF percentiles are clinically useful for this group. Secondly, early identification of babies at risk of hypoglycaemia (low %BF, AGA) is extremely important in preventing the devastating long-term neurological sequelae associated with hypoglycaemia.

As outlined above, an important limitation of our study is the possible under-representation of infants with low %BF. The exclusion of low birthweight infants (it is unit policy to admit all babies less than 2200 g to the nursery) and those too unwell for PEAPOD assessment (respiratory distress; low arterial cord pH) may have lower %BF, meaning our reference ranges may be skewed towards higher values. Mazehery et al.[5] have highlighted some of the statistical and biological shortcomings of %BF as an indicator of adiposity. We have continued to use %BF as it is the established parameter in our institution.

CONCLUSION

Low %BF is a risk factor for neonatal morbidity.[9] Accurate mean and quantile %BF references for a specific population are useful in determining babies at risk. We have presented the largest series for gender- and gestational-age-specific neonatal %BF. We have also demonstrated differences in body composition by maternal region of birth. We did not detect a relationship between arterial cord pH and %BF; however, we acknowledge that high-risk babies were likely not included due to a direct admission to the nursery.

AUTHOR CONTRIBUTIONS

T.L.L. and A.E.B. conceptualised and designed the study, coordinated and collected data, carried out some of the analyses, drafted the initial manuscript and reviewed and revised the manuscript. K.M. carried out the initial analysis and critically reviewed the manuscript. J.A.H. and A.G. conceptualised the study, supervised data collection and critically reviewed the manuscript. All authors approved the final manuscript as submitted and agree to be accountable for all aspects of the work.

ADDITIONAL INFORMATION

Competing interests: The authors declare no competing interests.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

REFERENCES

1. Carberry, A., Raynes-Greenow, C., Turner, R., Askie, L. & Jeffrey, H. Is body fat percentage a better measure of undernutrition in newborns than birth weight percentiles? *Pediatr. Res.* **74**, 730–736 (2013).
2. Crume, T. et al. Maternal fuels and metabolic measures during pregnancy and neonatal body composition: The Healthy Start Study. *J. Clin. Endocrinol. Metab.* **100**, 1672–1680 (2015).
3. Lingwood, B. et al. Prediction of fat-free mass and percentage of body fat in neonates using bioelectrical impedance analysis and anthropometric measures: validation against the PEA POD. *Br. J. Nutr.* **107**, 1545–1552 (2012).
4. Ellis, K. et al. Body-composition assessment in infancy: air displacement plethysmography compared with a reference 4-compartment model. *Am. J. Clin. Nutr.* **85**, 90–95 (2007).
5. Mazehery, H. et al. Air displacement plethysmography (pea pod) in full-term and pre-term infants: a comprehensive review of accuracy, reproducibility, and practical challenges. *Matern. Health Neonatol. Perinatol.* **4**, 4–12 (2018).
6. Urlando, A., Dempster, P. & Aitkens, S. A new air displacement plethysmograph for the measurement of body composition in infants. *Pediatr. Res.* **53**, 486–491 (2003).
7. Eriksson, B., Lof, M., Eriksson, O., Hannestad, U. & Forsum, E. Fat-free mass hydration in newborns: assessment and implications for body composition studies. *Acta Paediatr.* **100**, 680–686 (2011).
8. Deierlein, A., Thornton, J., Hull, H., Paley, C. & Gallagher, D. An anthropometric model to estimate neonatal fat mass using air displacement plethysmography. *Nutr. Metab.* **9**, 21–25 (2012).
9. Shaw, M., Lutz, T. & Gordon, A. Does low body fat percentage in neonates greater than the 5th percentile birthweight increase the risk of hypoglycaemia and neonatal morbidity? *J. Paediatr. Child Health* **55**, 1424–1428 (2019).
10. Hawkes, C. et al. Gender- and gestational age-specific body fat percentage at birth. *Pediatrics* **128**, 645–651 (2011).
11. Villar, J. et al. Body composition at birth and its relationship with neonatal anthropometric ratios: the newborn body composition study of the INTERGROWTH-21st project. *Pediatr. Res.* **82**, 305–316 (2017).
12. Yeh, P., Emary, K. & Impey, L. The relationship between umbilical cord arterial pH and serious adverse neonatal outcome: analysis of 51 519 consecutive validated samples. *BJOG* **119**, 824–831 (2012).
13. Malin, G., Morris, R. & Khan, K. Strength of association between umbilical cord pH and perinatal and long term outcomes: a systematic review and meta-analysis. *BMJ* **340**, 1471–1481 (2010).
14. Jeffery, H. Woman and babies: neonatal early assessment programme (NEAP). http://www.slhd.nsw.gov.au/rpa/neonatal%5content/pdf/guidelines/NEAP (2016).
15. Wood, A., Raynes-Greenow, C., Carberry, A. & Jeffrey, H. Neonatal length inaccuracies in clinical practice and related percentile discrepancies detected by simple length-board. *J. Paediatr. Child Health* **49**, 199–203 (2013).

16. McElduff, A. et al. The Australasian Diabetes in Pregnancy Society consensus guidelines for the management of type 1 and type 2 diabetes in relation to pregnancy. *Med. J. Aust.* **183**, 373–377 (2005).
17. United Nations Statistics Division. Methodology: standard country or area codes for statistical use (M49). http://unstats.un.org/unsd/methods/m49/m49.htm (1999).
18. Joseph, F. A. et al. A new approach to developing birth weight reference charts: a retrospective observational study. *Fetal Diagn. Ther.* **43**, 148–155 (2018).
19. Andersen, G. et al. Body composition from birth to 6 mo of age in Ethiopian infants: reference data obtained by air-displacement plethysmography. *Am. J. Clin. Nutr.* **98**, 885–894 (2013).
20. Andersen, G. et al. Fat and fat-free mass at birth: air displacement plethysmography measurements on 350 Ethiopian newborns. *Pediatr. Res.* **70**, 501–505 (2011).
21. Lee, A. C. et al. National and regional estimates of term and preterm babies born small for gestational age in 138 low-income and middle-income countries in 2010. *Lancet Glob. Health* **1**, e26–e36 (2013).
22. Davies-Tuck, M. L., Davey, M.-A. & Wallace, E. M. Maternal region of birth and stillbirth in Victoria, Australia 2000–2011: A retrospective cohort study of Victorian perinatal data. *PLoS ONE* **12**, e0178727 (2017).
23. Alexander, T. et al. Body composition of New-Zealand born term babies differs by ethnicity, gestational age and sex. *Early Hum. Dev.* **140**, 104924 (2020).
24. Stanfield, K. et al. Differences in body composition between infants of South Asian and European ancestry: the London Mother and Baby Study. *Int. J. Epidemiol.* **41**, 409–418 (2012).
25. Yajnik, C. S. et al. Neonatal anthropometry: the thin-fat Indian baby. The Pune Maternal Nutrition Study. *Int. J. Obes. Relat. Metab. Disord.* **27**, 173–180 (2003).
26. West, J. et al. UK-born Pakistani-origin infants are relatively more adipose than white British infants: findings from 8704 mother–offspring pairs in the Born-in-Bradford prospective birth cohort. *J. Epidemiol. Community Health* **67**, 544–551 (2013).
27. United Nations Children's Fund (UNICEF), World Health Organization (WHO). *UNICEF-WHO Low Birthweight Estimates: Levels and Trends 2000–2015* (World Health Organization, Geneva, 2019).
28. Paley, C. et al. Body fat differences by self-reported race/ethnicity in healthy term newborns. *Pediatr. Obes.* **11**, 361–368 (2015).
29. Au, C. et al. Body composition is normal in term infants born to mothers with well-controlled gestational diabetes mellitus. *Diabetes Care* **36**, 562–564 (2013).