

From Measurement to Meaning: Neonatal Growth and Development in Biological Anthropology

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Abstract

The neonatal period is a uniquely sensitive window of human development in which growth, physiology, and early-life environments intersect to shape survival and longer-term health. Biological anthropology contributes to neonatal growth research by integrating population variation, life-history theory, developmental plasticity, and the social and ecological contexts in which reproduction and early care occur. This review outlines how measurement choices and analytic approaches shape our understanding of neonatal growth and development across biological and social dimensions. This review summarises key indicators, compares the strengths and limitations of growth standards versus population references, and describes how birth registries and longitudinal cohorts address complementary questions. Transitions between biological, clinical, and contextual perspectives are highlighted to demonstrate how data and theory inform one another. It then reviews the determinants of neonatal size and early growth trajectories across maternal, placental, foetal, and socioecological levels, noting how inequality and healthcare context can influence risk and resilience. Special attention is given to infants born preterm and to size-for-gestational-age classification, where timing, proportionality, and postnatal adaptation complicate interpretation of single measurements and motivate trajectory-based approaches. Finally, we consider the application of neonatal growth assessment to clinical and public health practice, stressing transparency, local validation, and equity-aware interpretation. Together, these perspectives present a coherent view of neonatal growth as a complex and multifaceted biological and social process that can inform both research and care.

Keywords: neonatal growth, neonatal body size, preterm birth, growth trajectories, population variation

Introduction: why neonatal growth matters

The neonatal period – the first 28 days after birth – is a brief but decisive transition in human development. In this window, infants transition from placental dependence to independent breathing, feeding, thermoregulation, and immune adaptation, as well as functional maturation. Because multiple physiological systems are reorganising and adapting simultaneously, neonatal growth is highly plastic: it is shaped not only by prenatal conditions but also by the immediate postnatal environment, including caregiving practices and access to healthcare. Small differences in early growth can therefore have significant consequences, as they shape survival

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in the short term and are increasingly linked to later growth patterns, neurodevelopment, and long-term health outcomes. For these reasons, neonatal growth measures inform clinical care and also serve as population indicators of well-being, inequality, and early-life environment.

Biological anthropology provides a complementary lens to neonatal growth research by examining not only *how* infants grow, but also *why growth varies* across populations and settings [1]. It frames neonatal size and early growth as outcomes of life-history trade-offs [2] – between maternal investment and constraints, foetal demands, and the energetic costs of maintaining vital functions, as well as rapid development after birth. This perspective foregrounds context: nutrition, infection burdens, stress, and healthcare environments shape early growth patterns, and these influences are often socially patterned, producing gradients by socioeconomic position, migration, and structural inequality. By linking biology with lived conditions, biological anthropology helps interpret neonatal measures as more than clinical numbers, offering population-level insight into developmental plasticity and the environments into which children are born [3].

Determinants of neonatal growth: a layered perspective

Determinants of neonatal size and early growth can be organised as a layered system in which maternal characteristics and exposures shape placental development and function, which in turn condition foetal growth and maturation, all embedded within a wider socioeconomic, ecological, and healthcare context. Thus, the same birth size outcome can arise through different pathways (e.g., nutritional constraint, placental insufficiency, inflammation), and the effects of individual risks are often modified by timing in pregnancy and by access to effective prevention and care [4].

At the maternal level, stature and body composition reflect both genetic potential and accumulated life-course conditions, while nutrition, micronutrient status, and anaemia influence substrate availability for foetal growth. Maternal metabolic health (including glucose regulation) can push growth in either direction, contributing to growth restriction in some contexts and excessive foetal growth in others. Inflammatory states and infections can impair placental function and trigger earlier delivery, and behavioural factors such as smoking and alcohol exposure add direct foetal and placental stress. Parity and interpregnancy interval further shape risk through maternal physiological adaptation and nutrient depletion. Importantly, these influences interact: for example, undernutrition can increase susceptibility to infection, and stress can compound inflammatory and metabolic dysregulation, so risk is typically cumulative rather than attributable to a single cause [4,5].

The placenta mediates most maternal influences on foetal growth; variation in placental development, perfusion, and transport capacity can constrain growth even when maternal nutrition is adequate. Multiple pregnancy adds competition for resources and increases the likelihood of both growth restriction and preterm birth. Foetal characteristics also matter: male and female fetuses differ modestly in size distributions and may exhibit varying vulnerabilities to specific stressors, so sex-specific assessment enhances both comparability and interpretation [4,5].

Finally, maternal and placental pathways operate within a wider context that structures exposure and buffering. Socioeconomic inequality influences diet quality, housing, physical workload, and the ability to access timely antenatal care. Importantly, apparent differences in birth weight (BW) between ethnic groups may largely reflect these social determinants: in our

previous studies, BW differences were minimal when maternal education levels were comparable [6]. Other environmental factors – such as air pollution, seasonal infection patterns, and climate-related food insecurity – can shift both foetal growth and timing of birth, often with differential effects across populations and regions. Migration may alter risk through changes in nutrition, access to healthcare, social support, and exposure to stress. Across settings, the availability and quality of antenatal and neonatal services modify how these risks translate into outcomes, making healthcare access a key determinant of both neonatal size and early growth trajectories [4,5]. Because determinants operate through multiple pathways, accurate and standardised measurement is essential for linking biological and social processes to clinical outcomes.

Growth standards, references and comparability

A newborn's health status is partly reflected in body size at birth. But interpreting neonatal measurements requires particular caution. Accurate measurement and interpretation of BW, length, and head circumference (HC) against appropriate tools are therefore essential for clinical care and for identifying infants at risk of adverse growth-related outcomes. In this context, growth standards and population reference charts are indispensable tools for consistent assessment and informed clinical decision-making.

Growth standards are prescriptive, reflecting expected growth under conditions intended to support optimal development, and are primarily used as a benchmark for comparing populations and healthcare contexts. Growth references are descriptive: they summarise observed growth in a defined population at a particular time and are primarily used for interpreting individuals against their local population distribution, supporting population surveillance, and informing local clinical and public health decisions. However, there is still no global consensus on the most appropriate growth standards for assessing newborns, especially those born preterm. Intrauterine charts, which are widely used, remain controversial – particularly for infants with very low BWs [7] preterm infants have numerous physiological and developmental concerns, including growth and the provision of adequate nutrients to sustain growth. Growth is an important health care outcome measure for VLBW infants. Provision of energy and nutrients at levels to support growth and development is the goal of nutrition support for VLBW infants. Anthropometry and laboratory data are useful components of growth and nutrition assessment. The objectives of this paper are to describe: 1. Postnatal charts capture longitudinal growth more directly; however, they can also reflect local clinical practices and feeding strategies, rather than biology alone [8]. A related debate concerns *customised* versus *population-based* references: while customisation aims to account for maternal and pregnancy characteristics, its added value and interpretability have been questioned, and population-based approaches remain widely used [9,10].

A related question is whether newborn size should be assessed using global or regional references. International standards for newborn size and physical status have been recently proposed [11]; however, their adoption has been limited, and this should be considered with caution, as they require validation before implementation [12,13] based on the prevalence of small or large for gestational age (SGA/LGA). Our work demonstrated that population-based centiles derived from national datasets more accurately reflect the neonatal size and health status of newborns compared to global standards [12,14].

From single measurements to growth dynamics

Neonatal growth research draws on both the type of data available and the modelling tools used to translate measurements into interpretable metrics. The choice of study design determines which questions can be answered, while the choice of statistical approach determines how reliably results can be compared across time, settings, and populations.

Birth registries and longitudinal cohorts answer different questions. Population-based birth registries offer large numbers and near-complete coverage, making them ideal for describing distributions of birth size, estimating the prevalence of small for gestational age (SGA, when BW <10th centile for gestational age) and large for gestational age (LGA, when BW >90th centile for gestational age) births, monitoring trends, and comparing regions or sociodemographic groups. Their main limitation is depth: most include limited information on postnatal growth, feeding, and clinical course. Longitudinal cohorts and clinical follow-up datasets, in contrast, collect repeated measurements and richer context, allowing researchers to characterise postnatal growth patterns, identify critical windows, and link early trajectories to later outcomes.

To make findings usable in both research and practice, these datasets are commonly summarised using centiles, z-scores, and trajectory models. Much neonatal growth research relies on centile modelling, which converts large datasets into smoothed, gestational-age- and sex-specific centile curves and z-scores. Classic implementations include the LMS method and its extensions, as well as more flexible frameworks such as GAMLSS, both of which are widely used to construct reference curves [15,16] and which deals quite generally with skewness which may be present in the distribution of the measurement (e.g. height, weight, circumferences or skinfolds). While centiles and z-scores provide a cross-sectional snapshot, repeated measurements enable assessment of growth as a dynamic process – capturing changes in an infant's trajectory over time rather than position at a single time point. Trajectory approaches – ranging from mixed-effects growth-curve models to SITAR (SuperImposition by Translation And Rotation) [17] – summarise individual growth patterns with interpretable parameters (size, timing, and velocity), which can better match biological processes and clinical decision points than single-time-point cut-offs. These methodological considerations become especially critical for preterm infants, whose early adaptation and clinical care make growth interpretation complex and highly time-dependent.

Infants born preterm: heterogeneous trajectories

Preterm birth is a heterogeneous condition with profound implications for growth, development, and health across the life course. Interpreting early growth requires attention to expected neonatal physiology: many newborns lose weight in the first days after birth before sustained weight gain begins, and both the magnitude and timing of this nadir vary with GA as well as delivery mode and feeding context [19,20]. Against this background, preterm infants remain at increased risk of postnatal growth restriction, often followed by catch-up growth during the first 2–3 years [21]. Nonetheless, average adult stature tends to be lower than that of term-born peers, particularly among those born extremely preterm; however, findings differ across cohorts and settings, with some studies reporting convergence in adult size and pubertal timing among very, moderately, and late preterm groups [22,23,24].

Within preterm populations, birth size further stratifies risk. Lower BW commonly predicts a longer compensatory growth period and more persistent deficits, while being SGA adds an

additional burden of adverse perinatal outcomes and vulnerability [25,26] grade 3–4 intra-ventricular haemorrhage (IVH). Survivors born at the earliest gestations (<26 weeks) often remain shorter and lighter into adulthood and may exhibit a higher BMI, suggesting that growth “catch-up” can coexist with altered body composition or energy balance [24]. Together, these patterns underline why preterm growth should be approached as trajectories rather than single centile categories.

Our longitudinal work illustrates this trajectory-based perspective [18]. Using the SITAR model to analyse BW, height, and BMI from birth to 12 years, we found that BW exerted a stronger and more sustained influence on height and weight trajectories than GA, whereas GA played a more dynamic role in BMI, with sharper BMI increases after adiposity rebound in the early preterm groups (particularly among boys). This suggests partly distinct pathways: BW may better capture in utero energy and growth constraint relevant to linear growth and mass, while GA may shape later patterns of weight-for-height and obesity risk. Consistent with this, boys showed more pronounced long-term deficits, especially in weight and BMI. Finally, growth trajectories are closely aligned with broader health trajectories: our related work indicates a substantial burden of early-life multimorbidity among preterm-born individuals, concentrated in the first 7 years of life and strongly patterned by lower BW, which supports the need for personalised, multidisciplinary follow-up that integrates growth monitoring with wider health surveillance [27].

Size-for-Gestational-Age classification in context: timing, mechanisms, and overlap

As already mentioned, classifying neonatal body size identifies two higher-risk groups: SGA and LGA. SGA includes constitutionally small infants and those with intrauterine growth restriction, whereas LGA often reflects excessive growth linked to maternal factors. Importantly, SGA/LGA status must be interpreted in relation to GA, and even small errors in GA estimation can shift infants across BW-for-GA categories, altering who is labelled as SGA or LGA and complicating comparisons across populations and datasets.

This gestational context is also biologically informative: foetal growth follows a predictable pattern, with rapid cellular hyperplasia early in gestation, combined hyperplasia and hypertrophy up to around 32 weeks, and predominantly cellular hypertrophy thereafter [28]. As a result, the meaning of being classified as SGA depends on timing. Growth restriction early in gestation (affecting hyperplasia) is more likely to have lasting consequences, whereas later-onset restriction (affecting hypertrophy) may be partly reversible if severe hypoxic–ischaemic injury is avoided. Infants born SGA at very early gestations – particularly before 32 weeks – therefore face higher risks of death and major morbidity [25]. Clinically, it is also useful to distinguish mild SGA (often constitutional smallness) from more severe growth restriction; infants below the 3rd centile generally warrant closer attention. Appropriate neonatal charts are essential in this context; poor chart choice can misclassify risk and delay follow-up [29]. In our previous study, regional population-based centiles provided a closer fit to the observed newborn size distribution than international standards and produced materially different prevalence estimates of SGA/LGA classifications, including approximately a two-fold difference among term infants [12].

This GA-based framing also aligns with current mechanistic understanding. Preterm birth and foetal growth restriction are increasingly viewed as related endpoints of shared pathways to a healthy newborn, with placental development and function at the centre. Pregnancy

exposures such as undernutrition, infection or maternal illness, psychosocial stress, and harmful environmental exposures may converge through inflammation, oxidative stress, impaired immune protection, and placental dysfunction – limiting foetal growth, shortening gestation, or both [4].

From a population-health perspective, this overlap means that SGA should not be considered in isolation. Newborn vulnerability is often captured by intersecting constructs – preterm birth, SGA, and low birth weight (LBW – and any single definition can underestimate the total at-risk group. The Lancet Series therefore recently introduced the umbrella term *small vulnerable newborn* (SVN), defined as any liveborn infant who is preterm (<37 weeks), SGA or LBW (<2500 g), and proposed a simplified risk-oriented grouping into preterm non-SGA, term SGA (most reflecting foetal growth restriction), and preterm-SGA, with the highest mortality risk in preterm-SGA [30]. This framework complements SGA/LGA classification by making overlap explicit and strengthening comparisons and prevention strategies. The following sections translate these findings into practice, considering how measurement and interpretation inform risk assessment, care, and surveillance.

Applications, translation, and future directions

Neonatal growth assessment has clear applications in both clinical care and public health. In clinical settings, gestational-age- and sex-specific evaluation supports early risk stratification, guides feeding and monitoring decisions, and informs counselling – particularly for preterm and growth-restricted infants, where risk is heterogeneous. At a population level, routinely collected birth size data support surveillance of size-for-gestational-age patterns and related vulnerability profiles, monitoring of temporal trends, and evaluation of preventive and care interventions across regions and sociodemographic groups.

Translation into practice depends on understanding what charts and indicators can – and cannot – deliver. Misclassification may arise from imprecise GA estimation, differences in measurement timing, and the choice between international standards and local references. Responsible use, therefore, requires transparent reference choice, explicit acknowledgement of uncertainty, and attention to equity, since a single tool may perform differently across populations and can systematically under- or over-identify risk in disadvantaged groups. For these reasons, clear documentation of methods and local validation are as important as statistical fit.

A particular strength of neonatal growth research is its interdisciplinary foundation. Collaboration across biological anthropology, evolutionary medicine, obstetrics, neonatology, paediatrics, epidemiology, and public health improves interpretation and implementation by linking mechanisms and lived context with clinical pathways and population outcomes. Looking ahead, progress will depend on strengthening measurement harmonisation and metadata capture, wider adoption of trajectory-based approaches that connect neonatal patterns to longer-term outcomes, and continued attention to representativeness and bias when applying tools across settings.

Conclusion: towards integrated neonatal growth science

Neonatal growth assessment represents an intersection of biology, medicine, and social context. An integrated approach – combining robust measurement with context-aware interpretation – can improve both scientific inference and real-world decision-making, supporting

neonatal care that is effective, equitable, and grounded in the environments into which children are born.

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