World variation in head circumference for children from birth to 5 years and a comparison with the WHO standards

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ABBREVIATIONS

CDC	Centers for Disease Control and Prevention
MGRS	Multi-centre Growth Reference Study
UK	United Kingdom
US	United States of America
USPCN	Primary Care Network, the United States of America
WHO	World Health Organization

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AUTHORSHIP/CONTRIBUTORSHIP STATEMENTS
Hui LL conceptualized and designed the study, carried out the data analysis and drafted the initial manuscript.

HO Frederick K carried out the data analysis and critically review the manuscript.

DENG HB reviewed the literature and extracted the data.

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ABSTRACT

Objective

A recent review reported that the WHO 2006 growth standards reflect a smaller head circumference at 24 months than seen in 18 countries. Whether this happens in early infancy and to what extent populations differ is not clear. This scooping review aimed to estimate the rates of children in different populations identified as macrocephalic or microcephalic by WHO standards.

Methods

We reviewed population-representative head circumference-for-age references. For each reference we calculated the percentages of head circumferences that would be classified as microcephalic (<3rd WHO centile) or macrocephalic (>97th WHO centile) at selected ages.

Results

Twelve references from eleven countries/regions (Belgium, China, Ethiopia, Germany, Hong Kong, India, Japan, Norway, Saudi Arabia, UK and USA) were included. Median head circumference was larger than that for the Multicentre Growth Reference Study populations in both sexes in all these populations except for Japanese and Chinese children aged one month and Indians. Overall, at 12/24 months 8-9% children would be classified as macrocephalic and 2% would be classified as microcephalic, compared to the expected 3%. However at one month, there were geographic differences in the rate of macrocephaly (6-10% in Europe vs 1-2% in Japan and China) and microcephaly (1-3% vs 6-14% respectively).

Conclusions

Except for Indians and some Asian neonates, adopting the WHO head circumference standards would over-diagnose macrocephaly and under-diagnose microcephaly. Local population-specific cut-offs or references are more appropriate for many populations. There

is a need to educate healthcare professionals about the limitations of the WHO head circumference standards.

(247 words)

INTRODUCTION

Head circumference is routinely measured at well-baby clinics for health monitoring, in particular screening for pathological macrocephaly and intracranial expansive conditions. (1) Head circumference exceeding the 95th or 97th centile of the head circumference-for-age reference is the most commonly used criterion to determine unusually large head size, i.e. macrocephaly, for referral or follow-up.

A review of head circumference charts published in the 1960s concluded that there were "no significant racial, national, or geographic differences in head circumference". (2) In 2006, the World Health Organization (WHO) launched the growth standards for children from birth to 5 years (WHO standards), stating that they describe "how children should grow when not only free of disease but also when reared following healthy practices such as breastfeeding and a non-smoking environment". (3) As such, the WHO standards, including the head circumference-for-age charts, have been claimed to be suitable for use in all children, regardless of ethnicity. However increasing evidence suggests that the WHO standards over-diagnose macrocephaly from birth to 3 or 5 years in Norway, Belgium, (4) and the United Kingdom (UK). (5) A longitudinal study of breastfed infants from birth to 12 months in China and a retrospective study of United States (US) infants from 3 days to 2 years observed that the over-diagnosis of macrocephaly by the WHO standards increased with age, (6, 7) while a study in Ethiopia (8) reported larger discrepancies in the early months than at 2 years, suggesting the discrepancies are population- and/or age- specific.

A systematic review showed that mean head circumference z-score at 24 months from 18 of 26 countries was 0.5 standard deviations (SD) higher than the median of the WHO standards, leading to the standards over-reporting macrocephaly and under-reporting microcephaly. (9)

The review did not investigate population-specific differences in head size in early infancy, despite the first 10 months being an important time when increased head circumference can indicate raised intracranial pressure. (1) Thus a review over the age range from birth is warranted to examine the implications of using the WHO standards in younger children, and the potential risks for misdiagnosis of macrocephaly and microcephaly.

Here we carried out a scooping review on population-specific head circumference-for-age references, comparing them with the WHO standards at the median, 3rd and 97th centiles. In contrast to the review by Natale and Rajagopalan (9) which worked with raw data, we compared modelled references to reflect the population differences in head circumference.

METHODS

We searched for population-specific head circumference-for-age references from electronic databases/search engines PubMed, Google, Google Scholar and Baidu (for the Chinese literature). We included references based on population-representative samples for any age between birth and 5 years, excluding only those that did not include LMS values for computation of z-scores. We contacted some of the corresponding authors requesting LMS values or age-specific z-score tables where they were unpublished. We extracted and summarized information including sample size, age range, selection criteria, ethnicity, year of data collection and measurement method from each included reference.

To compare population-specific references with the WHO standards, we first identified the 3rd, 50th and 97th head circumference centiles of the WHO standards at 0, 1, 3, 6, 9, 12, 18, 24, 36, 48 and 60 months for boys and girls. (Table 1) We then calculated reference-age-sex-specific z-scores for these centiles (Y) relative to each of the population-specific growth references by substituting the reference LMS values in the formula:

$$z = \frac{(\frac{Y}{M} - 1)^L}{SL}$$

Each z-score was then converted to a centile assuming normality, and this centile was interpreted as the percentage of individuals in that population with a head circumference less than the corresponding WHO centile. Where the LMS values were not available at the selected ages, we linearly interpolated values using the R package "akima". For studies that did not publish their LMS values, the LMSfit function in the R package "sitar" was used to estimate them from the published centiles.

Macrocephaly was defined as head circumference >97th WHO centile, i.e. z-score >1.88 SD, while microcephaly was defined as head circumference <3rd WHO centile, i.e. z-score <-1.88 SD. These cut-offs were chosen to highlight population-specific differences, rather than using more extreme cut-offs, e.g. ±3 SD as used for clinical screening purposes. All statistical analyses were carried out using R (version 4.2.2).

RESULTS

We found 25 head-circumference-for-age references from Europe (Belgium, Germany, Norway, UK, Switzerland, the Netherlands, Sweden, Turkey, Finland, Hungary, Greenland and France), Asia (India, Japan, China, Hong Kong), Africa (Egypt and Ethiopia) and the Middle East (Saudi Arabia), South America (Colombia) and the USA. The sample characteristics (including sample size, age range, selection criteria and ethnicity), year of data collection and measurement method for head circumference for each of the references and the WHO standards are summarised in the Supplementary Table (web only data). We excluded the Greenland reference as it was based on few measurements at each age. We excluded all references lacking LMS values or age-specific z-score tables (7, 10-22) with the exception of the India reference as it was one of the study countries for the MGRS. (11) However we excluded age 0-1 months for the India reference because it recruited infants aged 0 to 15 days and only measured once every 3 months. Twelve references (Belgium, (23) China, (24) Ethiopia, (25) Germany, (26) Hong Kong, (27) India,(11) Japan, (28) Norway, (29) Saudi Arabia, (30) UK (31) and CDC,(32) & USPCN (6) in USA) were included in the comparison.

The majority of included head circumference references were developed for children from birth (except 1 month for Hong Kong) to young childhood, with some (e.g. UK, Germany, Belgium and Norway) extending to adolescence or adulthood (16-21 years) while some extending only to 2-3 years (Ethiopia, CDC2000 and USPCN2000). The majority were constructed in the 1990s-2000s, with the earliest measurements collected in the 1960s (CDC2000) and 1970s (UK1990). Non-stretchable plastic or paper tape was mainly used for measuring head circumference, while metal tape was used in MGRS, Norway and Euro-Growth.

Figure 1 displays the 97th (Figure 1A), 50th (Figure 1B) and 3rd (Figure 1C) WHO centiles for head circumference from birth (or 1 month and 3 months respectively for Hong Kong and India) to 24/36/60 months relative to the 12 references, in boys and girls separately. The same head circumference at the same age for the same sex corresponded to a wide range of centiles according to the reference used, with the widest range at birth for the 50th centile (25th to 76th in boys and 13th to 74th in girls), at 3 months for the 3rd centile (0.7th to 30th in boys and 0.4th to 21st in girls), and at 24 months for the 97th centile (67th to 99.9th in boys and 74th to 99.4th in girls. For the majority of references, head circumference plotted at a lower centile than the corresponding WHO centile except India, particularly boys, indicating their smaller head circumference in general. Head circumference in Japan, China and Saudi Arabia was at a higher centile only at 1 month, indicating head size was larger in these populations compared to the MGRS population, except in early infancy.

On average the rates of macrocephaly as assessed by the 12 references were 7.0%, 8.1% and 9.4% at 1 month, 12 months and 24 months. (Figure 2) The rate was as high as 23% in boys and 15% in girls at 1 month in CDC2000, and exceeded 20% in both boys and girls at 12 and 24 months in UK1990, according to WHO.

For microcephaly the rates were all <1.5% at 12/24 months except for India, Saudi Arabia, Japan, Ethiopia and CDC2000. At 1 month the rates were higher for China (6.2% in boys; 5.8% in girls), Japan (14% in boys; 14% in girls) and Saudi Arabia (18% in boys; 12% in girls), compared to the 1-3% observed in Europe. On average more children would be classified as microcephaly at 1 month (5.7%) compared to 12 months (1.9%) and 24 months (2.0%). (Figure 2)

The differences in mean and extreme head circumference in children 2-5 years old were similar to those observed at 24 months, with little variation by age.

DISCUSSION

This review of population-specific head circumference references shows that the WHO standards tend to overestimate head size in children under 5 years, except for Japanese and Chinese neonates where head size is smaller. This means that adopting the WHO standards would over-diagnose macrocephaly and under-diagnose microcephaly among children under 5 years, particularly in European countries. The magnitude of the difference in relative head size compared with WHO standards varies from birth to 24 months, indicating that a simple shift in cut-offs to define microcephaly and macrocephaly cannot fully resolve the over- and under-diagnosis.

Consistent with a recent review, (9) our comparison of population-specific head circumference references found that the WHO standards overestimated median head size and the rate of macrocephaly. Our results were also in line with the overestimation in macrocephaly previously reported from 0-2 years in Ethiopia, (8) 0-5 years in Norway, Belgium (4) and 0-3 years in the UK (5) and rapid head growth in the first 6-9 months. (5) We have extended these findings by showing that head size in the first month was smaller in some Asian countries than the MGRS population. Since our review was restricted to large population-specific head circumference references, the findings are likely to be more population-representative. Although some references were developed from data collected several decades ago, the over-diagnosis of macrocephaly will only be more conservative, given the secular trend to increasing head size. (17) We have however excluded countries that have not published head circumference references and those without LMS/z-score tables (India (11) being the exception). We also assumed the references were correctly modelled and smoothed and that they reflected the head circumference distribution in the population. Of note, the extremely small head size among infants aged 1 to 9 months in Saudi Arabia suggests possible sampling or measurement bias. However, this will also make the over-indication of large head size more conservative.

So far there has been no satisfactory explanation for the smaller head size in the MGRS populations. The potential role of poorer nutrition can be ruled out among the highly selected MGRS sample with optimal growth, or the “growth achievers”,(33) attributable to the drop out of the lighter exclusively breastfed infants.(34) MGRS used metal tape while most other studies used plastic non-stretchable tape. However, the Norway reference used metal tape and obtained different centiles from the WHO standards, and a field test among UK children suggested the deviation was unlikely solely due to the MRGS measurement technique. (35) Ethnic differences in skull morphology were unlikely to explain smaller head size in the MRGS populations, as carefully discussed by Natale and Rajagopalan. (9)

The MGRS working group justified the use of universal growth standards firstly based on studies on length/height in 1970s using data from the US, the UK, Australia and Japan (36) and secondly on the data from six MGRS study sites. (37) While ethnic differences in length/height in infants and young children are due to differences in genetic potential or environmental factors are debatable,(38) the idea that a "standard" or a "prescriptive" growth chart could be extrapolated to head size is not well grounded. The head circumference references included in this review were mainly from Europe so we were unable to assess ethnic differences more widely. However, there are indications that infants in some Asian countries may have relatively smaller heads in the first month of life, though not later, while Indians, particularly boys, may have smaller heads at all ages before 5 years. A more recent study among 0-2-year-old Indian infants from middle to upper income groups similarly reported WHO standards classified 26% boys and 14% girls as microcephalic (< - 2SD). ***(39)*** These observations in Asian children differ from those among European and particularly UK children who had larger heads than the WHO standards from birth. Such population differences are consistent with the review finding similar head size at 24 months in geographically proximal countries. (9) The smaller head size of Asian and South Asian neonates may be partly attributed to differences in maternal height (40) as maternal height is positively related to pelvic size (41) and smaller head size at birth could be an adaptive mechanism to facilitate birth in shorter women.

Implications

Measuring head circumference is a universal practice in well baby clinics, and the diagnostic characteristics of head circumference have important public health implications. The overestimation of relative head size with the WHO standards will exaggerate macrocephaly, (42) referring healthy children unnecessarily and wasting healthcare resources, (6) while under-reporting microcephaly will miss important morbidity, e.g. Zika virus infection. Inconsistent differences compared to the WHO standards by age also imply the need to apply locally relevant cut-offs for referrals or, where possible, develop local references for head circumference.

Given the observed ethnic differences in head size, there has already been advocacy for using population-specific references in clinical settings, instead of the WHO standards, in Ethiopia, (8) Norway, and Belgium (4) or calling for caution when using WHO standards in India (39) and in the UK. (5) In particular, in the UK, where the greatest exaggeration of macrocephaly from birth to 3 years and rapid head growth in the first 6-9 months was observed, recommendations have been to use other indicative signs together with the WHO cut-offs (which were adopted for use in the UK in 2009) for deciding whether referral is required. (5)

However, even population-specific head circumference references are poor at identifying pathological macrocephaly, with low sensitivity and specificity in the Netherlands (43, 44) and the US. (42) Conditioning on parents' head size, using adult head circumference references may improve test sensitivity by avoiding misclassifying infants with genetically large heads to be at risk of hydrocephalus. Rapid growth in head size, particularly when seen with other neurological signs or symptoms, is the strongest predictor of hydrocephalus, which is the commonest and most important cause of macrocephaly. (1) Since premature neonates are at higher risk of hydrocephalus, gestation-age-specific head circumference references are important for diagnosis in premature infants. Thus the use of change in head circumference centile, taking into account parental head size and gestational age, should improve test sensitivity and specificity. (44) Nevertheless, conditions associated with head enlargement do not always increase the occipital-frontal circumference. (6) Educating clinicians on the proper use of head circumference measurements and their limited role as diagnostic tools is important. (45)

Conclusions

Apart from some Asian countries in early infancy, adopting the WHO standards overestimates relative head size in young children aged 0-5 years, over-diagnosing macrocephaly and under-diagnosing microcephaly. The use of local population-specific head circumference cut-offs or references may be necessary to reduce misdiagnosis.

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"What is already known on this topic"

- Measuring head circumference is a universal practice post-natally and in well baby clinics.
- The diagnostic characteristics of head circumference have important public health implications.
- A recent review reported that the WHO 2006 growth standards reflect a smaller head size at 24 months than seen in 18 countries.

"What this study adds"

- This review of population-specific head circumference references found the WHO 2006 growth standards overestimate head size in children under 5 years, particularly in European countries.
- Compared to WHO standards, Japanese and Chinese children had smaller head at birth but not after 2 months or older.
- Head size and head growth in children varied by age and population group.

"How this study might affect research, practice or policy"

- Adopting the WHO standards will over-diagnose macrocephaly and under-diagnose microcephaly among children under 5 years, particularly in European countries.
- Local population-specific cut-offs or references for head circumference are more appropriate for many populations.

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Table 1. Head circumference at 3rd, 50th and 97th centiles of the WHO growth standards at selected ages from birth to 60 months in boys and girls.

	Centile	0m	1m	3m	6m	9m	12m	18m	24m	36m	48m	60m
Boys	3rd	32.1	35.0	38.3	41.0	42.6	43.6	44.9	45.7	46.8	47.5	47.9
	50th	34.5	37.2	40.5	43.3	45.0	46.1	47.4	48.2	49.5	50.2	50.7
	97th	36.9	39.4	42.7	45.6	47.3	48.5	49.9	50.8	52.1	53.0	53.5
Girls	3rd	31.7	34.3	37.2	39.7	41.3	42.3	43.6	44.6	45.9	46.7	47.2
	50th	33.9	36.5	39.5	42.2	43.8	44.9	46.2	47.2	48.5	49.3	49.9
	97th	36.1	38.7	41.9	44.6	46.3	47.5	48.8	49.8	51.2	52.0	52.6

*For example, a 3-month-old Belgian boy with a head circumference of 38.3 cm (3rd centile of WHO standards) would have z=(((Y/M)-1)**L)/(L*S)= -2.19, i.e. the 1.4th centile, based on the Belgian reference (L=1; M=40.9; S=0.029 at 3 months).

Figure 1 Centiles (z-score scale) on 12 population-specific growth references that are equivalent to the head circumference measurement at 3rd, 50th and 97th centile of the WHO 2006 growth standards (MGRS).

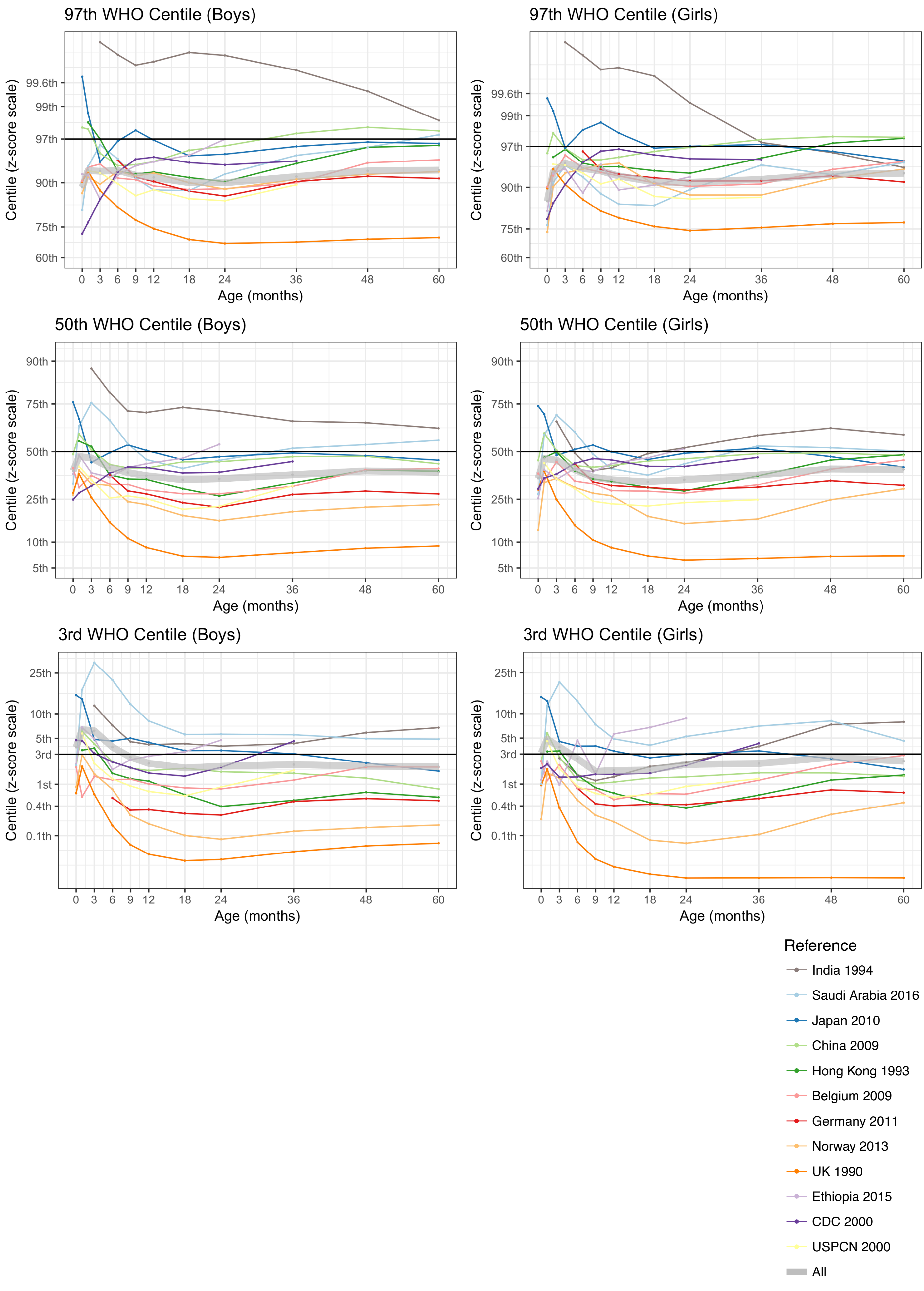
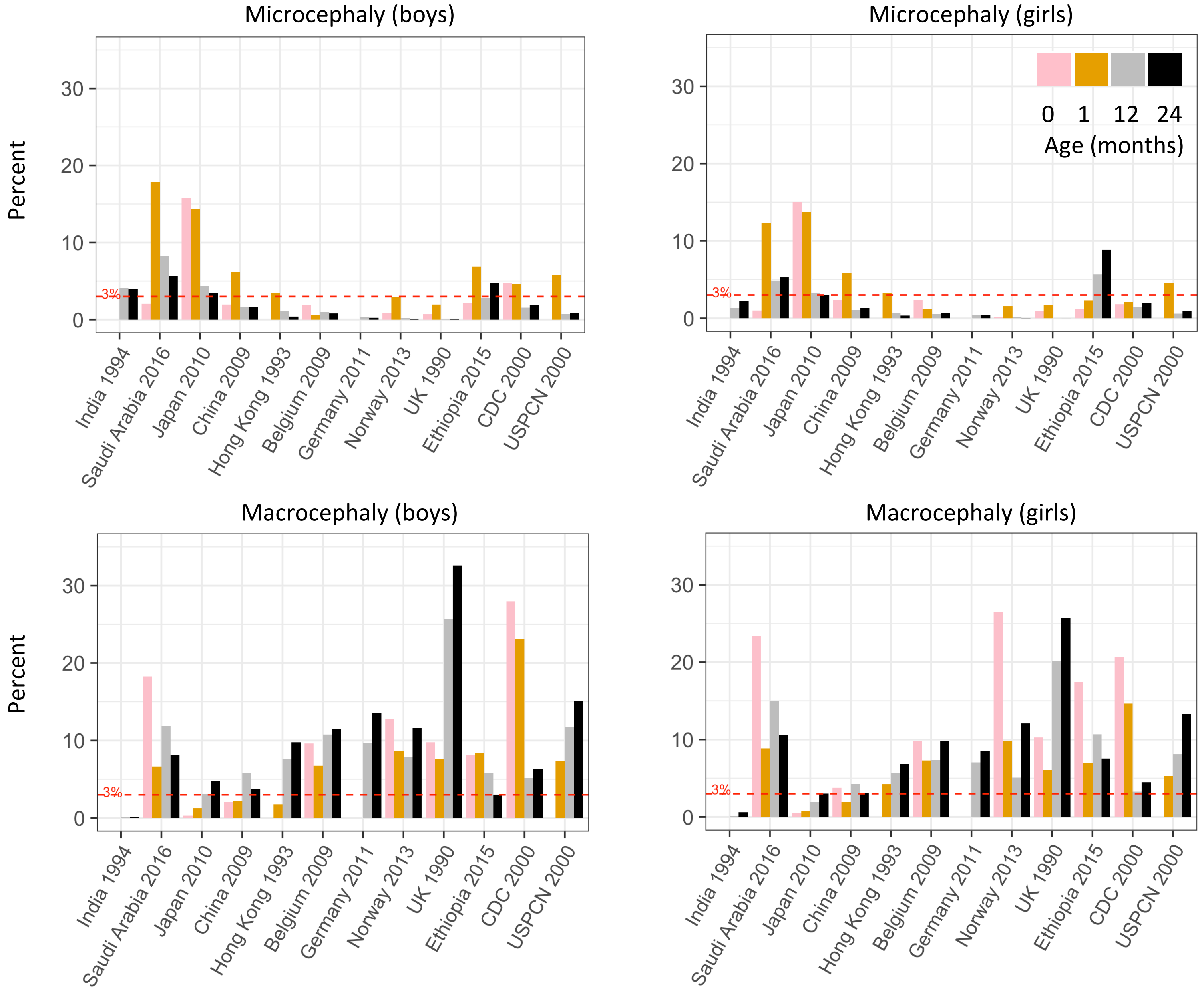


Figure 2. Percentages of macrocephaly (>97th WHO centile) and microcephaly (<3% WHO centile) estimated from population-specific growth references according to WHO standards at 0, 1, 12 and 24 months.



(Web only data) Table 2. Head circumference-for-age charts from the literature

HC Charts (Age range)	Country/region	Data source (year), type of measurements	Sample size and ethnicity	Subject exclusion criteria	Method in measuring head circumference (exclusion criteria)	Reference
WHO2006 (0-5y)	Pelotas, Brazil Accra, Ghana Delhi, India Oslo, Norway Muscat, Oman Davis, California, US	Multicentre Growth Reference Study (1997-2003) Longitudinal data for 0-2y Cross-sectional data for 2-5y	0-2y: 882; 2-5y: 6,669 (Multi-ethnicity)	– Familial low socio-economic status – Birth at altitude>1500m – Birth at <37weeks or 42 weeks or more – Multiple birth – Perinatal morbidities – Child health conditions known to affect growth – Maternal smoking during pregnancy or lactation – Breastfeeding for <12m – Introduction of complementary food before age 4m or after 6m	A self-retracting, 0.7 cm-wide, flat metal tape with blank lead-in strip (range, 0–200 cm, calibrated to 1 mm), was used to measure circumferences. Metal tapes were chosen because they are more robust and accurate, and stay in a single plane around the head.	WHO 2006(46)
Included						
Saudi Arabia2016 (0-5y)	Saudi Arabia	Community-based survey (2004-2005) Cross-sectional data	0-6y: 15,516 5-20y: 19,763	– <32 weeks gestation – birth weight<2.5kg	The maximum head (skull) circumference was measured using a non-stretchable tape measure. The tape measure was passed around the forehead, fixed above the eyebrows and moved up and down around the occiput to obtain the maximum circumference.	El-mouzan et al., 2007(47); Shaik et al., 2016(30)
Japan2010 (0-6y)	Japan	A community-based growth survey (2010) Longitudinal data for 0-1m Cross-sectional data for 14d-6y	0-1m: 4,774 14d-6y: 7,652 (Japanese)	Not mentioned.	Measured along the line passing the glabella and external occipital protuberance. The measurement was to the nearest 0.1 cm using a plastic measure. (Exclusion: values larger or smaller than 0.01% among the distribution of the data)	Kato et al., 2014(28)

HC Charts (Age range)	Country/region	Data source (year), type of measurements	Sample size and ethnicity	Subject exclusion criteria	Method in measuring head circumference (exclusion criteria)	Reference
China2009 (0-7y)	China (9 Urban cities, Beijing, Shanghai, Harbin, Xi'an, Nanjing, Wuhan, Guangzhou, Fuzhou, and Kunming)	4th National Survey on the Physical Growth and Development of Children in the nine Cities of China (2005) Cross-sectional data	0-7y: 34,901 boys and 34,859 girls (Chinese)	– temporary residents – history of premature birth birth weight less than – 2500g – acute illness within a month – chronic illness – obviously malnourished physically handicap	Measured to the nearest 0.1 cm using a flexible non-stretchable plastic tape over the most prominent part on the back of the head (occiput) and just above the eyebrows (supraorbital ridges). (Exclusion: Not mentioned)	Zong & Li 2013(24)
Hong Kong 1993 (5d-5y)	Hong Kong	A territory wide survey in kindergartens/ schools and 8 Maternal and Child Health Clinics in Hong Kong (1993) Cross-sectional data	5d-18y: 25,000 (Chinese)	– non-Chinese – not full-term	A non-stretch tape was used to measure head circumference.	Leung et al., 1996(27)
Belgium2009 (0-21y)	Flanders, Belgium	Well baby clinics, day care centres, school health services, universities, young employees in a centre for occupational medicine (2002-2004) Cross-sectional data	0-25y: 15,989 (Belgian origin)	– non-Belgian origin – children with known growth disorders, severe chronic disease – on medication that might affect growth – with uncertain origin or health status – premature births (for 0–3 years)	Measured with a non-stretchable glass fibre tape measurer (KAWE 43971). The tape measurer was placed in a straight line from the supra-orbital position to the largest protuberance at the back of the head. Caution was taken to clear the auricles before measuring. The head circumference was recorded to the last completed mm.	Roelants et al., 2009(23)
Germany2011 (0-18y)	Germany	The German Health Interview and Examination Survey for Children and Adolescents (KiGGS study, 2003-2006) Cross-sectional data	4m-17.98y: 17,158 (German)	– Preterm (<1y) – with medical conditions – medication possibly affecting growth	Measured by trained staff following standardized study procedures to the nearest 0.1 cm using a flexible, non-stretchable measuring tape (Siber Hegner, Ltd., Zurich, Switzerland). The maximum occipitofrontal head circumference of infants was measured in the supine position until 2y and for	Schienkiewiktz et al, 2011(26)

HC Charts (Age range)	Country/region	Data source (year), type of measurements	Sample size and ethnicity	Subject exclusion criteria	Method in measuring head circumference (exclusion criteria)	Reference
					ages 2 through 17y as well as for age 1y if lying measurement was not tolerated.	
Norway2013 (0-16y)	Norway	Bergen growth study (2003-2006), involving well-baby clinics, kindergartens and schools and birth data (YOB:1999-2003) from the medical birth registry Cross-sectional data	0-19y 7,291 children	– with one or both parents from outside Northern Europe (11%) – with chronic diseases that could affect growth (for instance coeliac disease or juvenile rheumatoid arthritis) – congenital anomalies – premature birth	A Lufkin W606PM metal measurement tape was placed just above the glabella and around the largest protuberance of the head by an observer positioned laterally to the child. The tape was firmly pulled to compress hair and the head circumference was recorded to the last completed mm.	Juliusson et al., 2013(29)
UK1990 (0-17/8y)	UK	A longitudinal growth survey and health records from three sources (1972-1994): – Edinburgh Growth Study (longitudinal, born in 1971-76) – Whittington Hospital (cross-sectional data of infants of 33-44 weeks gestation) – Cambridge Infant Growth Study (cross-sectional data of infants of 4 weeks – 2 years) – Cambridge Rosie Premature Neonates (cross-sectional data of infants of 32-44 weeks gestation)	0-17/18y: 6,444 boys; 4,917 girls (White)	Not mentioned	Not mentioned besides Edinburgh growth study followed the methods by Tanner 1962 (Exclusion: outside ± 5 SD)	Cole et al., 1998(31)
Ethiopia2015 (0-2y)	5 cities (Addis Ababa, Mekele, Dessie, Nazret and Dire Dawa) in Ethiopia	Health centres (2009-2013) Cross-sectional data	4,019 (multi-ethnicity)	– having a parent with a non-Ethiopian ethnic background – a history of chronic illness or visible malnutrition problems – suspected or diagnosed intracranial expansive condition – known congenital conditions related to head or brain	Measured as the maximal fronto-occipital circumference with a disposable paper measuring tape to the nearest 0.1cm. The measurement was repeated 3 times and the mean value was used. (No exclusion criteria)	Amare et al., 2015(25)

HC Charts (Age range)	Country/region	Data source (year), type of measurements	Sample size and ethnicity	Subject exclusion criteria	Method in measuring head circumference (exclusion criteria)	Reference
				– previous treatment for intracranial lesions		
CDC2000 (0-3y)	US	Four national surveys, i.e. NHESIII (1966-70), NHANES I (1971-74), NHANES II (1976-80) and NHANES III (1988-94) and head size at birth from Fels Longitudinal Study data (1960-1994)	Sample size not mentioned	– birth weight<1500g	Based on procedures used in the previous NHES and NHANES surveys, and either the same or comparable measuring equipment was used across the surveys. (Exclusion: extreme)	2000 CDC Growth Charts for the United States: Methods and Development, 2002(32)
USPCN2000 (3d -2y)	3 Mid-Alantic states, US	Electronic health records with head circumference measurements from Aug 2001 to Jan 2008, from the urban/suburban primary care network (33 primary care practices)	3d-24m: 75,412 (total 415 458 observations; 51% white, 33% African American)	– Birth weight<1500g – <33 week gestation – with at least 2 visits and 1 head circumference measurement – health problems that could affect head circumference (such as hydrocephalus, chromosomal abnormalities, metabolic disorders, neurofibromatosis, intracranial bleeding, and brain tumors)	The measuring instrument varied according to site; paper, cloth, and fiberglass tapes, as well as loops, were used. Approximately half of the measurements were recorded in centimeters, to the nearest millimeter, and the other half were recorded in inches, to the nearest ⅛th inch. (Exclusion: measurements taken at sick visits; head-circumference values of <20 and >60 cm; absolute value of CDC *z* score > 3)	Daymont et al., 2010(48)
India1980 (0-6y)	India	Two cohorts (birth+15 days to 72 months old in 1985-1987)	2635 (Indians) belonging to the affluent population segments (urban)	-Any obvious socio-economic constraints that could be expected to impair growth	Tools were calibrated periodically.	Agarwal et al., 1994(11)
Not included						
Switzerland1989 (0-19y)	Switzerland	Longitudinal data from 0-20 years (DOB 1954-1956)	137 swiss boys and 137 swiss girls	– Not healthy – Birthweight < 2500g	A narrow (6mm) plastic tape calibrated in millimeters. Accuracy of the measuring tape was checked monthly. The tension of the tape was such that the hair was firmly pressed against the skull. The largest circumference was recorded.	Prader et al., 1989(10)

HC Charts (Age range)	Country/region	Data source (year), type of measurements	Sample size and ethnicity	Subject exclusion criteria	Method in measuring head circumference (exclusion criteria)	Reference
The Netherlands2000 (0-20y)	The Netherlands	Cross-sectional data	14500 Dutch	-Children with diagnosed growth disorders and those on medication known to interfere with growth. Children of non-Dutch parents, except if one parent was Dutch and the other West European	Not mentioned	Fredriks et al., 2000(12)
US2000 (0-7y)	The US	Combining 7 previous head circumference references	N.A.	N.A.	N.A.	Rollins et la., 2000(15)
Euro-growth 2000 (1m-3y)	12 countries in Europe UK, Ireland, Austria, Germany, France, Sweden, Italy, Spain, Portugal, Greece, Hungary, Croatia	A multicenter, longitudinal, observational study	1-36m: 2,245 who were measured on 20,696 occasions	– Gestation < 37 wks – Risk of intrauterine growth pathology, e.g. maternal diabetes or epilepsy – Birth weight < 2500 g – Unknown father – Not prepared to participate for planned study period – Unable to communicate with the site – No single birth – Congenital malformations – Inherited metabolic disease – Neonatal disease required hospitalization > 7 days – Chronic disease	A flexible, narrow steel tape was used. The tape was applied firmly around the head above the supraorbital ridges, covering the most prominent part of the frontal bulge anteriorly, and over the part of the occiput that gives maximum circumference.	van't Hof et al., 2000(13)
Sweden2002 (0-3.5y)	Goteborg, Sweden	Pupils in the final grade of school in 1992 (DOB 1973-1975) Retrospective study for retrieving longitudinal data	0-3.5y: 3650	– Prematurity – Postmaturity – No birth data – Chronic disease – Medical treatment	Not mentioned	Wikland et al., 2002(49)
Egypt2008 (1-2y)	Egypt	2002 Egyptian National Standard Growth Curve Project in the Greater Cairo area (2 maternal and child welfare centres and 72 private kindergartens; and older children and adolescents attending 13 fee-paying	1m-18y: 27, 826	– unhealthy – suffering malnutrition – overcrowding at home – not a normal delivery/pregnancy – abnormal birth weight – major genetic or organic diseases, which affect growth	Measurement of maximum head circumference using a non-stretchable tape	Zaki et lal, 2008(14)

HC Charts (Age range)	Country/region	Data source (year), type of measurements	Sample size and ethnicity	Subject exclusion criteria	Method in measuring head circumference (exclusion criteria)	Reference
		primary, preparatory and secondary grade schools and 4 private sports clubs) Cross-sectional data				
Turkey2012 (0-6y)	Family health centers in the city center and suburbs of Kayseri, Turkey	Children attending the family health service units, sampled by socioeconomic levels Cross-sectional data	0-6y: 2,989	– Not mentioned	Head circumference was measured with a nonelastic tape on a line passing over the glabella and the posterior occipital protrusion, with children aged 0-2 years lying on a bed, and children over 2 years of age standing up. Two health technicians took the measurements of head circumference twice, and the mean was used for analyses.	Elmali et al., 2012(16)
Finland2012 (0-7y)	Espoo, Finland	Primary health care providers Mixed cross-sectional data	0-7y: 19,715 (born in 1986–2008, 146,790 measurements in total)	– not full term – with diseases or medications potentially affecting growth.	Measured using a plastic tape measure at every visit to the child health clinic as the maximum occipitofrontal circumference, and the results are rounded to the nearest 0.1 cm (Exclusion: outside ± 5 SD, measurements which were obtained outside scheduled visits)	Karvonen et al., 2012(17)
Turkey2015 (0-18y)	Relatively well-off districts in İstanbul, Turkey	Data of infants and children attending the Well Child Clinic of the University Hospital (1992-2006) and school students Longitudinal data for 15d-60m and 6y to 18y	15d- 60m: 2,391 boys; 2,102 girls 6y-18y: 1,100 boys; 1,020 girls (Multi-ethnicity)	– preterm – unhealthy – children of families of low socioeconomic level	Measured with a narrow non-stretch tape placed in the horizontal plane encompassing the midpoint of the forehead between the eyebrows and hairline and the occipital prominence.	Neyzi et al., 2015(18)
Colombia2016 (0-4y)	Colombia	Both cross-sectional and longitudinal (an infant cohort	27 209 (Colombian)	-Not from middle and upper socio-economic level families; both parents of foreign	A non-distensible measuring tape was used	Duran et al. 2016(19)

HC Charts (Age range)	Country/region	Data source (year), type of measurements	Sample size and ethnicity	Subject exclusion criteria	Method in measuring head circumference (exclusion criteria)	Reference
		of 540 infants followed during the first year of life)		origin, any physical condition or medication affecting growth. Exclusion criteria for infant cohort: both parents of foreign origin, from multiple gestations, gestational age before week 37 or after week 42 or birth weight below 2500 g. Also cases with complications or maternal use of alcohol, tobacco or illicit substances during pregnancy		
China2016 (0-1y)	60 communities in twelve cities in China	Follow-up study on healthy breastfed infants living in an “optimal” conditions (during 2007-2010) Longitudinal data	0-12m: 1,840 (measured at birth, weekly during the first month after delivery, and monthly from two to twelve months of age, Chinese)	Not fulfilling the following inclusion criteria For mother: maternal age 20-35years old, height ≥ 1.5 m, without pregnancy complications, nonsmokers For infant: singleton, 37-42 week gestation, birth weight of 2.5-4kg, free of serious conditions at birth, without significant morbidity For feeding: 1) exclusive or predominant breastfeeding for 4-6m; 2) introduction of complementary foods at 4-6m; and 3) continuing partial breastfeeding to 12m.	Standard protocol without detail description	Huang et al., 2016(50)
Hungary2016 (0-18y)	Hungary	A longitudinal growth survey	2984 boys and 2701 girls born between 1980 and 1983	Not fulfilling the following inclusion critieria: born with a weight between 2500 and 4500 grams and who were not suffering from any long-lasting or severe disease that would have influenced their growth and development	The steel measuring tape is held around the child’s head in such a way that it passes through the glabella landmark point at the front, through the opistocranion landmark point at the back, and over the maximum bulge of the occiput.	Jouberrt & Gyenis 2016(20)

HC Charts (Age range)	Country/region	Data source (year), type of measurements	Sample size and ethnicity	Subject exclusion criteria	Method in measuring head circumference (exclusion criteria)	Reference
Greenland2018 (0.25-2y)	Nuuk and Ilulissat, Greenland	Two pregnancy and birth cohort studies (Greenland Inuit Child Cohort born in 1999 and Climate Changes, Environmental Contaminants and Reproductive Health Cohort born in 2002) Longitudinal data (through data linkage)	0.25-2y: 279	– <37 or 42+ week gestation	A common plastic centimetre tape measure was used.	Klovgaard et al., 2018(21)
France2021 (0-5y)	France	Automatically extracted data for individual paediatric patients from electronic medical records between 1990 and 2018	157,762 children	-Children (n=4,883) with an excessive number of growth measurements after age six months	Not mentioned (exclusion: absolute z-scores ≥ 5 standard deviations (SDs) based on WHO growth charts and aberrant z-score variations between two successive measurements)	Bergerat et al., 2021(22)

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