15/7/2026

Dear ESA selection committee,

Letter of support for Dr Rebecca Goldstein and A/Prof Aya Mousa: Submission for ESA Young Investigator Scientific Article Award

Eligibility:

Rebecca is an early career researcher and Aya is an early-mid career researcher. They are both active financial members of the ESA for at least 12 months. Rebecca is within 2 years of PhD and Aya is within 5 years of PhD. The research was predominantly in English.

Publication:

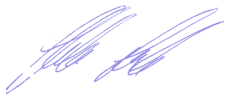
Gestational weight gain and risk of adverse maternal and neonatal outcomes in observational data from 1.6 million women: systematic review and meta-analysis

Both applicants' roles in research design, analytical work and writing and revision:

Rebecca was the first author in this publication, and other was joint senior author. I chair the WHO panel and highlighted the opportunity for this work. Rebecca and Aya conceived, designed, and led this project from inception to publication. They developed the research plan, established a multidisciplinary authorship team with expertise in evidence synthesis, obesity prevention, and research translation, and coordinated all stages of the review. Rebecca and Aya developed collaborations with international experts within the WHO GWG Technical Advisory group, incorporating them as co-authors. They led protocol development, designed and supervised data extraction and quality assessment, guided the statistical analysis, and shaped the interpretation of findings presented interim results to the WHO GWG Technical Advisory Group, integrating their feedback into the final analyses. They led manuscript drafting, revisions, and the submission process. Rebecca and Aya's intellectual leadership shaped the methodological approach, outcome selection, and framing of the global implications.

This publication has 18 authors, most of whom are international, including some from WHO, who require approval for signatures. In this case, we have provided signatures from local co-authors and myself, one of the senior authors (and corresponding author) have signed on behalf on the rest of the team.

Yours sincerely,



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President International Society Of Endocrinology
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Application for ESA Young Investigator Scientific Article Award

Role of applicant: Dr Rebecca Goldstein

As an ECR at 1.8 years post doc and an early NHMRC Early Career Investigator Fellow, Rebecca Goldstein is an endocrinologist and clinician leader at Monash Health. Knowledge impact includes >3470 citations, in JAMA and BMJ. Rebecca is a regular ESA member and her research focuses on obesity, diabetes and cardiometabolic risk and prevention in and beyond, using risk prediction and implementation.

Role of applicant: A/Prof Aya Mousa

As an EMCR at 5 years post-doc (relative to opportunity) and NHMRC research fellow, Aya Mousa has an exceptional track-record with >173 publications (138 since 2020; ~80% Q1) in international peer-reviewed journals (66 first/last author, 43 second/second-last author), including The BMJ, Lancet eclinmed and Nature Reviews Endocrinology. These have been cited >11400 times (individual papers with 2258, 934 and 768 citations, 15% >100 citations), highlighting their significant contributions to the field. Aya has been a regular ESA member and her research is at the forefront of endocrinology, focusing on insulin physiology and metabolic function in insulin-resistant states including pregnancy, obesity and polyendocrine metabolic ovarian syndrome, with the aim of improving precision prevention, diagnosis and treatment.

Impact of paper according to selection criteria:

Scientific quality of paper

Publication: **Gestational weight gain and risk of adverse maternal and neonatal outcomes in observational data from 1.6 million women: systematic review and meta-analysis**

BMJ 2025; 391 doi: https://doi.org/10.1136/bmj-2025-085710 (Published 19 November 2025)Cite this as: BMJ 2025;391:e085710

BMJ is a Q1 general medical journal with the highest impact factor in its category in 2025 (93.6). The article has an Altmetric score of 149, coverage by 18 news outlets, 11 citations, >10,000 views, and a Field-Weighted Citation Impact (FWCI) of 3.14.

Scientific/translational/clinical impact

Through our prior research in gestational weight gain (GWG), with high-impact systematic reviews doi:10.1001/jama.2017.3635 (altmetric 526, citations 1542) doi: 10.1186/s12916-018-1128-1), I was aware of the WHO initiative to develop GWG standards. Our mentor, Professor Teede, chairs the WHO panel and highlighted the opportunity for this work.

This publication provides the most comprehensive and contemporary global evidence on gestational weight gain (GWG) to date. It synthesises data from 1.6 million women across diverse regions and income settings, using a spectrum of body mass index (BMI) and GWG categories. It directly informs public health messaging and antenatal care by clarifying the risks associated with excessive GWG, particularly caesarean birth, hypertensive disorders, LGA and macrosomia.

It has shaped scientific understanding by quantifying the magnitude of GWG above and below recommended ranges. This is directly relevant to pregnancy lifestyle interventions to reduce excess GWG, recommended in Australia and by the US Prevention Task Force. With 5 of the 6 World Health Organisation (WHO) world regions represented, the work updates and substantially expands prior evidence, resolving uncertainties about neonatal outcomes and global applicability. Its early influence is reflected in strong engagement metrics (Altmetric 149, >10,000 views).

This research has translation impact for health system design, population and policy implication for prevention strategies, and global economic benefits. At a clinical level, these findings support the development of tailored, BMI-specific guidance for women and clinicians. At Monash Health, the findings underpin a multi-site implementation model (OptimaleMe), integrating evidence-based lifestyle intervention and digital health technology into routine antenatal care.

At a population level, this work directly informs the WHO Gestational Weight Gain Technical Advisory Group project: Development of Global GWG standards. The project addresses the gap of GWG standards and tools globally and aims to develop global standards that will be applied in millions of pregnancies globally, in a similar way to the global use of WHO child growth standard charts. My research meets the WHO objective of defining eligibility criteria for the inclusion of individual patient data (IPD) into the global pooled dataset that will generate new GWG standards.

https://www.who.int/teams/nutrition-and-food-safety/development-of-global-gestational-weight-gain-standards

This publication builds on our track records as an NHMRC early career research fellows and has significantly advanced our national and international profile in maternal health and GWG research. We were invited to present these findings among high impact researchers at the Monash University Sub-Faculty of Clinical and Molecular Medicine Research Symposium in November 2026.

This work has strengthened our collaborations with WHO and international experts, positioning us as a key contributor to global GWG standards and supporting our trajectories researchers leading impactful, translational maternal health research.

Applicants' roles in research design, analytical work and writing and revision

Rebecca was the first author in this publication, and Aya was the joint senior author. Rebecca and Aya conceived, designed, and led this project from inception to publication. They developed the research plan, established a multidisciplinary authorship team with expertise

in evidence synthesis, obesity prevention, and research translation, and coordinated all stages of the review. Rebecca and Aya developed collaborations with international experts within the WHO GWG Technical Advisory group, incorporating them as co-authors. They led protocol development, designed and supervised data extraction and quality assessment, guided the statistical analysis, and shaped the interpretation of findings presented interim results to the WHO GWG Technical Advisory Group, integrating their feedback into the final analyses. They led manuscript drafting, revisions, and the submission process. Rebecca and Aya's intellectual leadership shaped the methodological approach, outcome selection, and framing of the global implications.

Relevance to endocrinology

This work is highly relevant to endocrinology, as gestational weight gain reflects core hormonal and metabolic adaptations in pregnancy, including progressive insulin resistance, placental endocrine signalling, and adipose-derived metabolic regulation. By quantifying how deviations in GWG influence endocrine-mediated outcomes such as gestational diabetes, hypertensive disorders, and foetal overgrowth, this research strengthens the evidence base for metabolic risk-stratified antenatal care. The findings directly support endocrine-informed prevention strategies and contribute essential evidence to the WHO development of global GWG standards.

OPEN ACCESS

Check for updates

Gestational weight gain and risk of adverse maternal and neonatal outcomes in observational data from 1.6 million women: systematic review and meta-analysis

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Additional material is published online only. To view please visit the journal online.

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Accepted: 18 September 2025

ABSTRACT

OBJECTIVE

To synthesise evidence from contemporary populations (2009-24) across diverse world regions and income settings on associations between gestational weight gain (GWG) and broad clinical outcomes, to inform updated, globally relevant GWG standards.

DESIGN

Systematic review and meta-analysis.

SETTING

Observational studies in all languages, with >300 participants, reporting pregnancy outcomes stratified by body mass index (BMI) and GWG.

PARTICIPANTS

Women aged >18 years with singleton pregnancies.

MAIN OUTCOME MEASURES

Birth weight and rates of caesarean delivery, hypertensive disorders of pregnancy, preterm birth, small/large for gestational age infant, low birth weight, macrosomia, neonatal intensive care unit (NICU) admission, respiratory distress, hyperbilirubinaemia, and gestational diabetes.

RESULTS

Of 16 030 studies, 40 met inclusion criteria (n=1 608 711); 6% (n=65 114) of women had underweight, 53% (n=607 258) had normal weight, 19% (n=215 183) had overweight, and 22% (n=252 970) had obesity. GWG was below or above Institute of Medicine (IOM) or study specific recommendations in 23% and 45%, respectively. Using World Health Organization BMI criteria, GWG below IOM recommendations was associated with lower birth weight (mean difference −184.54, 95% confidence interval −278.03 to −91.06); lower risk of caesarean delivery (odds ratio 0.90, 0.84 to 0.97), large for gestational age infant (0.67, 0.61 to 0.74), and macrosomia (0.68, 0.58 to 0.80); and higher risk of preterm birth (1.63, 1.33 to 1.90), small for gestational age infant (1.49, 1.37 to 1.61), low birth weight (1.78, 1.48 to 2.13), and respiratory distress (1.29, 1.01 to 1.63). GWG above IOM recommendations was associated with higher birth weight (mean difference 118.33, 53.80 to 182.85); higher risk of caesarean delivery (odds ratio 1.37, 1.30 to 1.44), hypertensive disorders of pregnancy (1.37, 1.28 to 1.48), large for gestational age infant (1.77, 1.62 to 1.94), macrosomia (1.78, 1.60 to 1.99), and NICU admission (1.26, 1.09 to 1.45); and lower risk of preterm birth (0.71, 0.64 to 0.79) and small for gestational age infant (0.69, 0.64 to 0.75). For Asian BMI criteria, GWG below recommendations was associated with higher risk of hypertensive disorders of pregnancy (3.58, 1.37 to 9.39) and preterm birth (1.69, 1.25 to 2.30) and lower risk of large for gestational age infant (0.80, 0.72 to 0.89). GWG above recommendations was associated with higher risk of caesarean delivery (1.37, 1.29 to 1.46) and large for gestational age infant (1.76, 1.42 to 2.18) and lower risk of small for gestational age infant (0.62, 0.53 to 0.74) and low birth weight (0.44, 0.31 to 0.6).

CONCLUSIONS

This systematic review captured trends of rising maternal age and BMI from diverse world regions and income settings, with broad outcomes across all BMI groups. GWG outside IOM recommendations was associated with increased risk of adverse outcomes. These findings will help to inform the process of the WHO initiative to optimise globally relevant GWG standards for improved perinatal outcomes across world regions.

STUDY REGISTRATION

PROSPERO CRD42023483168.

WHAT IS ALREADY KNOWN ON THIS TOPIC

Gestational weight gain (GWG) outside recommendations is associated with adverse maternal and neonatal outcomes

Most countries rely on Institute of Medicine GWG guidelines, developed primarily from observational studies in the US and high income countries decades earlier

Recognising the need for more universal relevance, the World Health Organization is committed to developing contemporary global GWG standards for antenatal care across diverse settings and populations

WHAT THIS STUDY ADDS

This study captures a contemporary population of 1.6 million women with wide ranges of body mass index and GWG categories, across diverse world regions

GWG below recommendations was associated with lower birth weight and higher risk of preterm birth, small for gestational age infants, low birth weight, and respiratory distress

GWG above recommendations was associated with higher birth weight and higher risk of caesarean delivery, hypertensive disorders of pregnancy, large for gestational age infants, macrosomia, and neonatal intensive care admission

Introduction

Gestational weight gain (GWG) is independently associated with adverse maternal and neonatal outcomes, as well as long term health outcomes for

both mother and child.[1 2] It reflects a complex interplay of factors including maternal nutrition, fetal growth, amniotic fluid, maternal fat stores, and fluid retention.[3] In 1990 the Institute of Medicine (IOM) generated GWG guidelines,[3] aiming to optimise these outcomes. These guidelines were based on a modest sized population of predominantly white women from 1980 in the US, with a mean body mass index (BMI) of 24 and age of 26 years, focusing on the outcome of low birth weight.[4] The 2009 IOM guideline update incorporated World Health Organization BMI categories and broader outcomes, varying recommended GWG by maternal BMI.[5] These guidelines have since provided an important international reference point; however, the evidence underpinning them reflects the population and priorities of that era, characterised by lower maternal age and BMI, with limited ethnic diversity and a narrow high income setting. These limitations became apparent in subsequent efforts to appraise the IOM criteria internationally,[6 7] with substantial heterogeneity prompting the development of region specific GWG criteria.[8] Striking global population trends over the past two decades, indicating escalating maternal age, BMI, and GWG,[9] underscore the urgent need for updated GWG guidelines based on contemporary, ethnically diverse populations across low, middle, and high income settings and with broader outcomes to develop globally representative GWG standards.

In this context, our previous systematic review and meta-analysis captured data from 1999 to 2017 and showed that 47% of women had GWG above 2009 IOM recommendations.[5 10 11] Excess GWG was associated with 85-95% higher odds of a large for gestational age infant and macrosomia, 30% higher odds of caesarean delivery, and 23-34% lower odds of a small for gestational age infant and preterm birth. Conversely, GWG below recommendations, present in 23% of pregnancies, was associated with 40% lower odds of a large for gestational age infant and macrosomia but 50-70% higher odds of a small for gestational age infant and preterm birth. These associations with GWG were independent of maternal pre-pregnancy BMI. However, the available evidence was from primarily high income populations, with key gaps persisting around the capture of contemporary, ethnically diverse populations from broader settings and using a wider range of clinical outcomes.

The current WHO antenatal care guidelines recommend that women across all pre-pregnancy BMI categories have appropriate GWG according to the IOM recommendations.[5 12] Policy interventions have been shown to enable healthier lifestyles, prevent excess GWG, and improve outcomes.[13] Definitive systematic reviews and aggregate and individual patient data meta-analyses also provide clear evidence that individually targeted lifestyle interventions in pregnancy can reduce excess GWG and improve maternal and neonatal outcomes with demonstrated cost effectiveness.[14-19] On the basis of this evidence and aligned with WHO,[12] the US Preventive Services Task Force and other international organisations now recommend implementation of healthy GWG interventions in pregnancy.[20-22] However, implementing these interventions in contemporary and diverse populations and settings to mitigate adverse outcomes requires globally relevant GWG reference standards to accurately monitor and guide healthy GWG.

In response to this identified gap, WHO has launched an initiative to develop global GWG standards.[23] This includes creating a single individual patient data repository integrated from harmonised global data, with the aim of defining optimal GWG thresholds applicable across diverse settings. This WHO international initiative is supported by a technical advisory group composed of experts in maternal and neonatal healthcare, GWG, epidemiology, and statistical modelling.

To support this initiative, this study aims to close fundamental evidence gaps by examining associations between GWG and a wide range of clinical outcomes across contemporary populations, with a range of BMI and GWG categories and spanning diverse world regions and income settings. We also aim to capture diverse population characteristics, determinants of GWG, and reported outcomes, to support the process of the WHO GWG Technical Advisory Group in defining eligibility criteria, determinants, and maternal and child outcomes for the individual patient data sample that will be used to generate globally applicable GWG standards and optimal GWG ranges.

Methods

This systematic review and meta-analysis is informed by research priorities outlined at meetings of the WHO GWG Technical Advisory Group in 2023 and reported in accordance with PRISMA guidelines (supplementary file 1).[24] The aims, methods, and progress were presented at WHO GWG Technical Advisory Group project meetings in November 2023 and March 2024. The protocol was registered a priori with the International Prospective Register of Systematic Reviews (PROSPERO CRD42023483168).

Search strategy

We conducted systematic searches in electronic databases including Embase, EBM Reviews (via OVID), and Medline, Medline In-Process, and other non-indexed citations (supplementary file 2). We used a search string of relevant terms, aligned with our previous systematic review (supplementary file 3).[10] We manually searched bibliographies of relevant studies identified by the search strategy and relevant reviews/meta-analyses via backwards citation to identify additional studies. The search covered publications from 2009 to 8 November 2023, with an updated search on 1 May 2024. We applied no language restrictions.

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Screening and eligibility

We used Covidence systematic review software (Veritas Health Innovation, Melbourne, AU) as a reference manager to facilitate and track the screening of studies, which reviewers did manually by without using automation capabilities. A team of 10 reviewers screened studies by title and abstract and by full text. Two independent reviewers did duplicate screening on 20% of articles, and a third reviewer resolved discrepancies. Non-English articles were screened and translated by a native speaker within the systematic review team. We did not calculate inter-rater agreement statistics (for example, Cohen's κ) owing to the use of multiple rotating reviewer pairs, which precluded consistent pairing. However, before data extraction, we re-screened all studies marked as potentially eligible (n=353) to confirm final eligibility. Of these, 145 (41%) needed to be adjudicated by the project leads (RG, AM) owing to complexity or ambiguity in reporting, to ensure consistent application of screening criteria before final inclusion.

Observational studies in all languages, of singleton pregnancies in women aged over 18 years, and with a study population of more than 300 participants were eligible for inclusion (supplementary file 4). The minimum sample size was prespecified to minimise small study effects and reduce bias from imprecise or unstable estimates. We included studies that reported total GWG stratified by the pre-pregnancy BMI category as the exposure of interest. Any BMI categories or GWG cut-offs were acceptable, provided that the study reported the proportion of women with adequate, excessive, or insufficient GWG within one or more pre-pregnancy BMI categories. Total GWG was calculated on the basis of self-reported or measured pre-pregnancy weight (pre-conception or during the first trimester) and final gestational weight measured at the last prenatal visit or at the time of delivery. Outcomes needed to be stratified by study defined BMI and GWG categories. When studies lacked clarity about minimum maternal age (for example, often not specified in large database studies) or about GWG measurements or BMI/GWG stratification, we contacted authors twice for further information. We excluded studies that solely categorised by mean weight gain per week or that only adjusted for BMI and/or GWG in multivariable models. To ensure meaningful comparisons in light of the heterogeneity of data presented for GWG by BMI categories, we limited studies included in meta-analysis to those that used recommended GWG as the reference group within each pre-pregnancy BMI category and presented outcomes accordingly. Studies that did not meet this criterion were precluded from meta-analysis to avoid misclassification bias and preserve comparability, but we retained them in descriptive (narrative) synthesis to enhance the generalisability of our findings.

Data extraction

Selection of data and variables was informed by meetings of the WHO GWG Technical Advisory Group in 2023. Potential determinants of GWG identified in the literature were considered, including social/environmental (socioeconomic status, altitude, policies, health services) and maternal factors (parity, race/ethnicity, education, marital status, employment, height, sedentary behaviour, sleep, interpregnancy interval, dietary intake, micronutrient status, mental health, smoking and substance misuse, attitudes towards weight gain). Our previous experience showed that many of these variables were poorly captured, with varying definitions and weak clinical associations. Variables prioritised for extraction were race/ethnicity, education, and smoking status, along with study characteristics (sample size, country, setting, and so on) and all maternal and neonatal outcomes (proportions, odds ratios, and measures of spread).

For the purpose of this study, we examined immediate pregnancy outcomes. Maternal outcomes of interest included caesarean delivery, gestational diabetes mellitus, pregnancy induced hypertension, pre-eclampsia/eclampsia, postpartum haemorrhage, induction of labour, birth trauma, perineal tear, and prolonged second stage of labour, although not all outcomes were available for extraction and some were defined variably. Caesarean delivery was either not further specified or defined as both planned and emergency deliveries,[25] emergency only,[26] or combination of instrumental delivery and caesarean delivery into a single outcome.[27] Similarly, hypertensive disorders of pregnancy were defined as pre-eclampsia alone[28-30]; a combination of gestational hypertension, pre-eclampsia, and/or eclampsia[31-34]; or a combination of pre-pregnancy hypertension, gestational hypertension, and eclampsia[26]; or had no definition.[35] Here, we combined these definitions into single outcomes of caesarean delivery and hypertensive disorders of pregnancy. Neonatal outcomes were more consistently defined across studies and included preterm birth (birth at <37 weeks gestation; not further defined as spontaneous or iatrogenic), birth weight, small for gestational age infant (birth weight <10th centile, adjusted for gestational age with or without sex, according to population specific references), large for gestational age infant (birth weight >90th centile adjusted for gestational age with or without sex, according to population specific references), macrosomia (birth weight >4000 g), low birth weight (birth weight <2500 g), amniotic fluid abnormalities, neonatal intensive care unit (NICU) admission, stillbirth, neonatal morbidities, Apgar score, respiratory distress syndrome, hyperbilirubinaemia (jaundice requiring phototherapy), and neonatal length of stay in hospital. Long term outcomes including (but not limited to) postpartum weight retention, type 2 diabetes, childhood weight, and childhood cognition were collected but were beyond the scope of this study. Two independent reviewers cross checked all extracted data were for accuracy.

Risk of bias appraisal

We assessed risk of bias for each study in duplicate, using the Newcastle-Ottawa quality assessment scale for cohort studies.[36] Discrepancies were resolved by a third reviewer, with most assessments being accepted. The scale consists of three domains: selection (evaluation of the selection and representativeness of cohort population, ascertainment of exposure), comparability (of cohorts), and outcome (appropriateness of outcome assessment and follow-up processes). We awarded studies a maximum of one star for each numbered item within the selection and outcome categories and a maximum of two stars for comparability. We then used the tally of stars to classify each study as having high, fair, or low quality.[36]

Data synthesis strategy

We produced dichotomous outcome measures for each study by calculating the odds ratios and 95% confidence intervals. We calculated these by using the number of women within each BMI and GWG category (that is, GWG below, within, and above the recommended range) and the number of events (using the recommended GWG within each BMI category as the reference group). Where calculating the odds ratio from the available information was not possible, we used the odds ratio (95% confidence interval) reported in the published study. We used crude (unadjusted) data, to ensure comparability given variable control for confounding factors. We assessed effect sizes for continuous outcomes (for example, birth weight) by using weighted mean differences and associated 95% confidence intervals. When two or more studies assessed the same outcome, we used random effects models applying the restricted maximum likelihood method and Hartung-Knapp method for standard errors in the meta-analysis. We combined data across all BMI categories to obtain a pooled effect estimate for GWG below and above compared with within recommended GWG. We also analysed data within each specific BMI group and generated a pooled effect estimate for GWG below and above compared with within recommended GWG; results are reported in this sequence. Outcomes that were not meta-analysed are synthesised descriptively.

On the basis of our learnings from previous systematic reviews,[10 11] we specified stratified analyses a priori on the basis of GWG by the pre-pregnancy BMI category. The primary analysis examined studies using the WHO BMI categories separately from studies using the Asian BMI categories (table 1), with two separate pooled effect sizes calculated. We adopted this approach because many studies from Asia use lower BMI cut-offs to define overweight and obesity, reflecting the higher risk of adverse outcomes in Asian populations at lower BMI thresholds.[28 37] Combining WHO and Asian specific BMI thresholds into a single pooled analysis could mask these important population specific risk differences and may generate potentially misleading results and GWG recommendations.

We assessed heterogeneity by using the I^2 statistic, where I^2>50% indicated substantial heterogeneity.[38] We could not do meta-regression to investigate sources of heterogeneity (smoking status, mean age, nulliparity, ethnicity) because data for these covariates were not available in the required format (that is, stratified by GWG and pre-pregnancy BMI category). We did subgroup analysis for obesity subclasses when available (that is, obesity classes I, II, and III). Additionally, we did a sensitivity analysis using the Sidik-Jonkman method with Hartung-Knapp adjustment to assess the robustness of the findings,[29 39] particularly given the potential influence of small sample sizes and between study heterogeneity. We assessed publication bias by visual inspection of funnel plots and using Egger's test, where five or more studies were available for a given outcome. We did additional sensitivity analyses excluding studies that were assessed as being at high risk of bias and comparing studies using both adjusted and crude odds ratios. We defined statistical significance as two sided P<0.05. We used Stata software version 18 for analyses.

Patient and public involvement

Patients and the public were not involved in the design, conduct, dissemination, or evaluation of this study as this was a study level meta-analysis.

Results

Search results

The search identified 21 729 studies (20 893 in the initial search and 836 in the updated search). After removal of duplicates, we screened 16 030 by title and abstract. Of these, 2241 progressed to full text review, of which 124 potentially eligible studies did not provide information on the minimum age of participants and/or timing/method of GWG measurement. We contacted authors of these 124 studies by email for clarification; 22 responded and nine were eligible,

Table 1 | Different body mass index categorisations

Categorisation	Underweight	Normal weight	Overweight	Obesity
World Health Organization	<18.5	18.5-24.9	25.5-29.9	≥30
Metropolitan Life Insurance	<19.8	19.8-26.0	26.0-29	≥29
China*	<18.5	18.5-24.9	24-27.9	≥28
Thailand*	<18.5	18.5-22.9	23-24.9	≥25
Asia*	<18.5	18.5-22.9	23-24.9	≥25
Taiwan*	<18.5	18.5-24	≥24	-

*Combined into single group: Asian BMI category.

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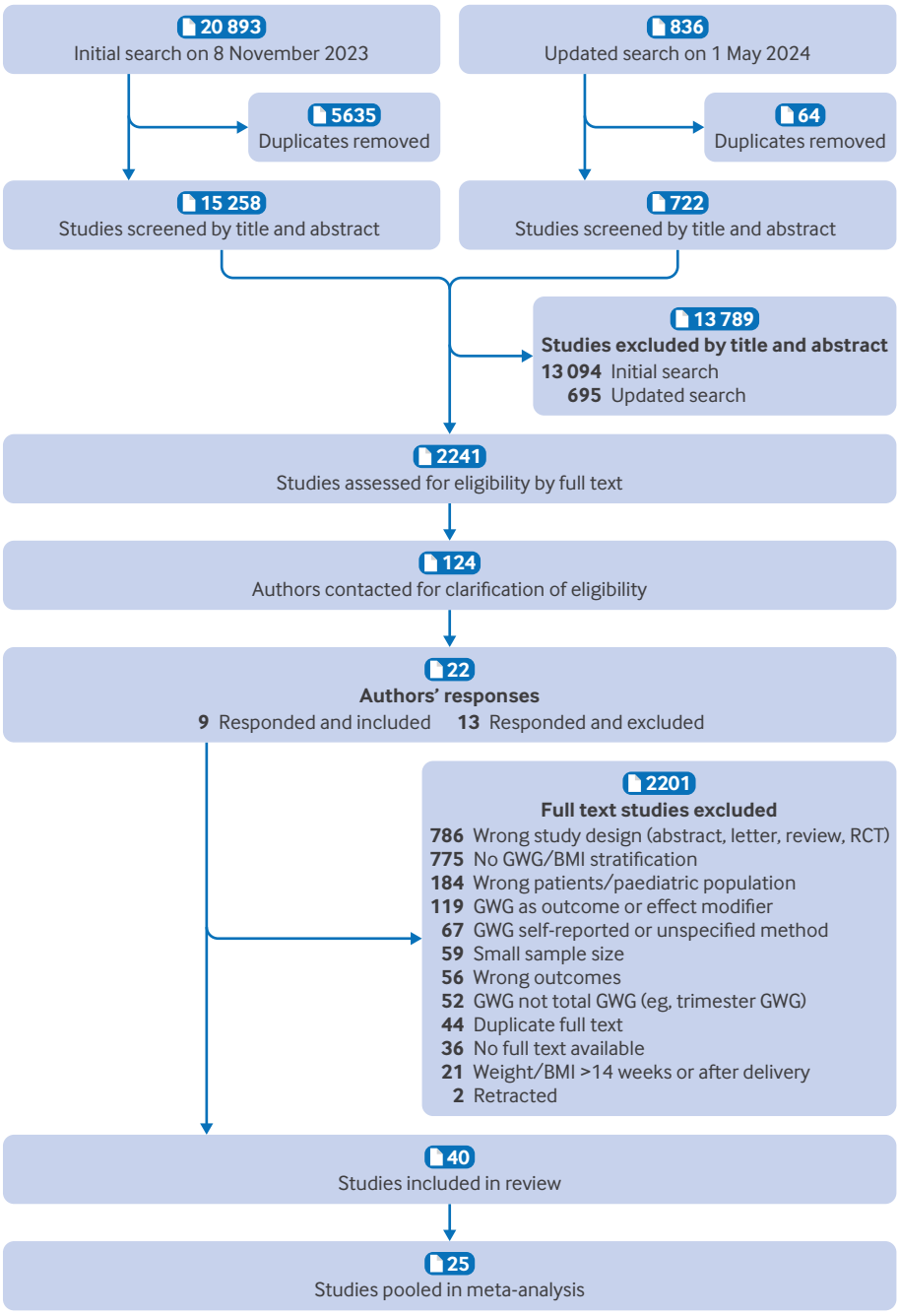

Fig 1 | PRISMA flow diagram of study selection. BMI=body mass index; GWG=gestational weight gain; RCT=randomised controlled trial

including three studies that provided data in the required format.[40 41 42] Overall, we excluded 2201 studies on the basis of full text review and included a total of 40 cohort studies, with participant data from 1 608 711 million women (fig 1). A list of excluded studies with reasons is available online (https://doi.org/10.26180/29878097.v1).

Study characteristics

Supplementary tables A and B provide the general and detailed characteristics of the 40 included studies.[25-27 30-35 40-70] Of the included studies, 25 were retrospective and 15 were prospective, with sample sizes ranging from 435 to 570 672. Included studies represent five of the six WHO defined world regions (fig 2), with nine studies from the American region (six from North America,[40 45 53 61 64 66] two from Brazil,[34 41] and one from Chile[42]), 17 studies from the Western Pacific region (14 from mainland China,[33 43 44 46 47 55 56 58-60 62 68-70] one each from Taiwan,[48] Japan,[49] and Vietnam[31]), three studies from the South-East Asian region (all from Thailand[27 65 67]); nine from the European region (three from Portugal[50 51 63] and one each from Spain,[52] Sweden,[52]

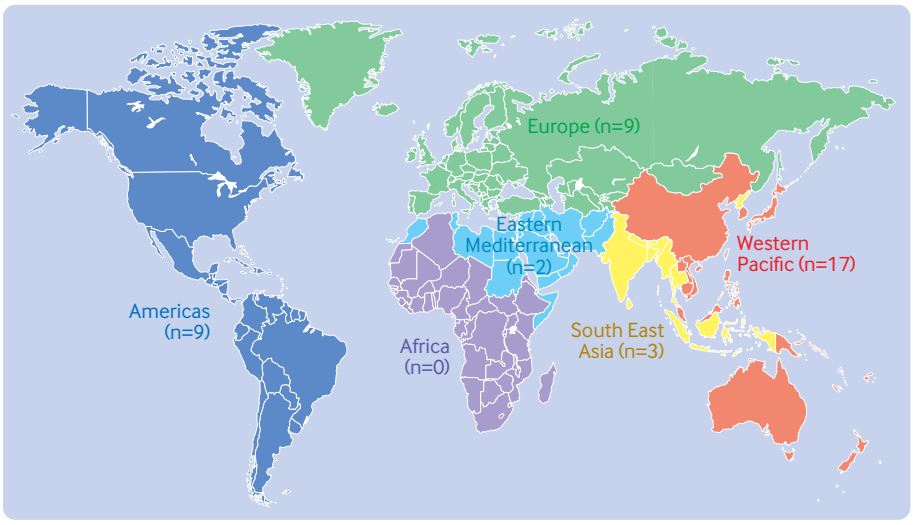

Fig 2 | Global representation of included studies classified by World Health Organization world regions

Germany,[25] Poland,[57] Belgium,[26] and Turkey[32]), and two studies from the Eastern Mediterranean region (both from Iran[30 54]). We found no studies from the African region.

Studies used different pre-pregnancy BMI categories, including WHO (n=27), Metropolitan Life Insurance tables (n=3), Chinese or other Asian classifications (n=9), and both WHO and Chinese (n=1). Different GWG categories were also used, including 2009 IOM (n=35), 1990 IOM (n=2), Asian specific categories (n=2), and study specific categories (n=1).

Across the 40 included studies, women with an underweight BMI comprised 6% (n=65 114) of the total sample, women with normal weight 53% (n=607 258), women with overweight 19% (n=215 183), and women with obesity 22% (n=252 970) (data available for 1 140 525 women) (on the basis of study defined BMI categories, including both WHO and Asian BMI categories). Studies that combined GWG groups (for example, combined underweight and normal weight[71] or combined overweight and obese[27 31 33 44 56 62]) were excluded from this count.

At the end of pregnancy, GWG was below recommended ranges in 23% (n=251 265), within recommended ranges in 32% (n=352 974), and above recommended ranges in 45% (n=493 146) across all pre-pregnancy BMI groups (data available for 1 097 385 women). Studies with incomplete data on GWG within each BMI group were excluded from this count.[25 27 35 59 71] Table 2 lists the GWG within each pre-pregnancy BMI category.

Risk of bias

Table 3 outlines the risk of bias assessments. Within the selection criteria, the exposed cohort was either truly representative or somewhat representative of the population (for example, cohort with obesity or with gestational diabetes mellitus) in 33/40 studies. Ascertainment of exposure (GWG) scored highly, and outcome assessment and follow-up were reported in all studies. Among the 40 studies, we considered 36 to be high quality; we considered four to be low quality,[32 42 50 62] largely owing to poor comparability. We included two of the studies judged as low quality in the overall meta-analysis and excluded them from sensitivity analysis by study quality to assess their influence on the results.[32 62]

Meta-analysis

A total of 25 studies reported data in the required format for pooling in meta-analysis,[25-27 30 32 34 40 41 44 45 47 50 53-55 57 58 61-64 66-68 70] with data on 1 442 343 women. All studies used IOM GWG criteria; two used IOM 1990,[30 54] and the remainder used IOM 2009. Of the 25 studies, 10 were conducted in Asia; five used WHO BMI categories,[47 55 58 67 68] four used Asian BMI categories,[27 43 44 62] and one used both.[70] Asian BMI criteria included Chinese[43 44 62 70] and Thai[27] BMI standards. Some studies using Asian BMI criteria combined overweight and obesity into one category[27 43 44 62]; we combined these BMI categories into one group of obesity and overweight in the meta-analysis. Of the remaining 15 studies conducted

Table 2 | Gestational weight gain (GWG) within pre-pregnancy body mass index (BMI) categories

Pre-pregnancy BMI category	GWG below recommended (%)	GWG within recommended (%)	GWG above recommended (%)
Underweight (n=40 176)	27	44	29
Normal weight (n=386 777)	24	36	40
Overweight (n=150 641)	14	23	64
Obese (n=163 628)	20	20	60

Studies that combined GWG groups (for example, combined underweight and normal weight or combined overweight and obese) and studies with incomplete data on GWG within each BMI group were excluded from this count.

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Table 3 | Risk of bias assessment for included studies

	Selection				Comparability	Outcome			
Source	Representativeness	Non exposed cohort	Ascertainment	Outcome	Covariates	Assessment	Follow-up	Lost to follow-up	Quality score
Ha	*	*	*	*	**	*	*	*	High
Jiang	*	*	*	*	*	*	*	*	High
Miao	*	*	*	*	**	*	*	*	High
Guo	-	*	*	*	**	*	*	*	High
Park	*	*	*	*	**	*	*	-	High
Araujo	*	*	*	*	**	*	*	*	High
Rosinha	*	*	*	*	*	*	*	*	High
Wilkins	*	*	*	*	**	*	*	*	High
Johansson	*	*	*	*	**	*	*	*	High
Chairat	*	*	*	*	**	*	*	*	High
Class	*	*	*	*	**	*	*	*	High
Asvanarunat	*	*	*	*	**	*	*	-	High
Hao	*	*	*	*	**	*	*	*	High
Devlieger	*	*	*	*	**	*	*	*	High
Badon	*	*	*	*	**	*	*	*	High
Tanigawa	*	*	*	*	**	*	*	*	High
Perea	*	*	*	*	**	*	*	*	High
Deputy	*	*	*	*	**	*	*	*	High
Tsai	*	*	-	*	**	*	*	*	High
Zhang	*	*	*	*	**	*	*	*	High
Huang	*	*	*	*	**	*	*	-	High
Li	*	*	*	*	**	*	*	-	High
Guan	*	*	*	*	-	*	*	*	Low
Mastroeni	*	*	-	*	**	*	*	*	High
Miao	*	*	*	*	**	*	*	*	High
Chang	*	*	*	*	**	*	*	*	High
Wei	-	*	*	*	*	*	*	*	High
Somprasit	*	*	*	*	**	*	*	*	High
Yang	*	*	*	*	*	*	*	*	High
Gante	*	*	*	*	*	*	*	*	High
Lewandowska	*	*	*	*	**	*	*	*	High
Panahandeh	*	*	*	*	**	*	*	*	High
Yazdanpanahi	*	*	-	*	*	*	*	*	High
Weschenfelder	*	*	*	*	**	*	*	*	High
EraslanSahin	-	*	*	*	-	*	*	*	Low
Mardones	*	*	*	*	-	*	*	*	Low
Santos	-	*	*	*	-	*	*	-	Low
Wen	*	*	*	*	*	*	*	-	High
Yan	-	*	*	*	**	*	*	*	High
Zhang	-	*	*	*	**	*	*	*	High

Studies were awarded maximum of one star for each numbered item within selection and outcome categories and maximum of two stars for comparability. Tally of stars was then used to classify each study as having high, fair, or low quality.

outside of Asia, 13 used WHO BMI criteria and two used Metropolitan Life Insurance tables.[30 54] When we could not calculate the odds ratio from the available information, we used the odds ratio (95% confidence interval) reported in the published study.[34 53 57 63 66 67] Supplementary table C provides information on instances in which we calculated odds ratios or retrieved them from publications and whether these were crude or adjusted.

Of the extracted outcomes, meta-analyses were possible for the following 11 outcomes: caesarean delivery, hypertensive disorders of pregnancy, preterm birth, small for gestational age infants, large for gestational age infants, low birth weight, macrosomia, NICU admission, birth weight, respiratory distress syndrome, and neonatal jaundice. Table 4, figure 3, and figure 4 show the pooled odds ratios for individual maternal and neonatal outcomes by pre-pregnancy BMI categories, according to the WHO classification, for those with GWG below and above IOM recommendations. Table 5, figure 5, and figure 6 show the pooled odds ratios for individual maternal and neonatal outcomes by pre-pregnancy BMI categories, according to an Asian classification, for those with GWG below and above IOM recommendations. Table 6, figure 7, figure 8, and figure 9 show the pooled odds ratios for individual maternal and neonatal outcomes by obesity class for weight loss during pregnancy and for GWG below and above IOM recommendations. Forest plots for individual outcomes by BMI group are provided in supplementary figures A-E.

Maternal outcomes

Caesarean delivery

Twelve studies (n=126 733) assessed caesarean delivery.[25 26 27 32 45 58 62 63 64 67 68 70] In studies using WHO

Table 4 | Summary of outcomes by World Health Organization body mass index categories for gestational weight gain (GWG) below or above recommended

Outcome	No of studies	No of women	GWG below recommended				GWG above recommended			
			OR (95% CI)	I^2 (%)	P value*	Direction	OR (95% CI)	I^2 (%)	P value*	Direction
Maternal outcomes										
Caesarean delivery:										
Underweight <18.5	3	6879	0.90 (0.37 to 2.18)	83.26	0.03		1.49 (1.18 to 1.88)	0	0.47	Higher risk
Normal weight 18.5-24.9	5	42 159	0.97 (0.9 to 1.04)	0	0.54		1.36 (1.32 to 1.40)	0	0.94	Higher risk
Overweight 25-29.9	4	8504	0.93 (0.87 to 0.98)	0	0.99	Lower risk	1.40 (1.15 to 1.71)	0	0.36	Higher risk
Obese ≥30	9	65 098	0.85 (0.75 to 0.95)	16.54	0.13	Lower risk	1.29 (1.09 to 1.52)	54.38	0.01	Higher risk
Overall	10	122 640	0.90 (0.84 to 0.97)	38.99	0.03	Lower risk	1.37 (1.30 to 1.44)	17.82	0.08	Higher risk
HDP:										
Underweight <18.5	2	2594	0.80 (0.32 to 1.95)	0	0.72		1.16 (0.59 to 2.25)	0	0.82	
Normal weight 18.5-24.9	3	24 522	0.74 (0.26 to 2.11)	61.11	0.07		1.59 (1.41 to 1.78)	0	0.78	Higher risk
Overweight 25-29.9	3	11 302	0.94 (0.81 to 1.10)	0	0.9		1.36 (1.19 to 1.56)	0	0.79	Higher risk
Obese ≥30	6	52 547	1.00 (0.88 to 1.22)	0	0.23		1.31 (1.14 to 1.50)	43.78	0.28	Higher risk
Overall	6	90 965	1.00 (0.93 to 1.08)	0	0.3		1.37 (1.28 to 1.48)	40.2	0.31	Higher risk
Neonatal outcomes										
Preterm birth:										
Underweight <18.5	3	6879	2.37 (0.66 to 8.52)	78.76	0.01		0.79 (0.68 to 0.91)	0	0.97	Lower risk
Normal weight 18.5-24.9	5	42 159	1.64 (1.30 to 2.06)	39.07	0.2	Higher risk	0.62 (0.52 to 0.73)	14.88	0.52	Lower risk
Overweight 25-29.9	4	8504	1.49 (0.87 to 2.55)	20.5	0.41		0.72 (0.49 to 1.04)	20.93	0.38	
Obese ≥30	6	9277	1.43 (0.87 to 2.33)	60.02	0.07		0.84 (0.72 to 0.99)	0	0.8	Lower risk
Overall	7	66 819	1.63 (1.33 to 1.90)	69.27	0	Higher risk	0.71 (0.64 to 0.79)	22.45	0.45	Lower risk
SGA:										
Underweight <18.5	5	38 837	1.56 (1.14 to 2.12)	80.8	0	Higher risk	0.58 (0.52 to 0.64)	3.9	0.56	Lower risk
Normal weight 18.5-24.9	8	359 047	1.65 (1.56 to 1.75)	11.5	0.57	Higher risk	0.78 (0.66 to 0.93)	82.18	0	Lower risk
Overweight 25-29.9	5	144 172	1.36 (1.28 to 1.44)	0	0.74	Higher risk	0.66 (0.53 to 0.81)	30.54	0.34	Lower risk
Obese ≥30	10	215 460	1.31 (1.21 to 1.41)	0	0.25	Higher risk	0.72 (0.69 to 0.76)	0	0.61	Lower risk
Overall	14	757 516	1.49 (1.37 to 1.61)	79.99	0	Higher risk	0.69 (0.64 to 0.75)	83.16	0	Lower risk
Low birth weight:										
Underweight <18.5	2	720	3.36 (0.24 to 46.97)	0			0.40 (0.15 to 1.08)	0		
Normal weight 18.5-24.9	4	3882	1.79 (1.04 to 3.09)	0	0.27		0.82 (0.25 to 2.66)	61.57	0.03	
Overweight 25-29.9	2	986	1.31 (0.30 to 5.76)	0	0.74		1.17 (0.98 to 1.40)	0	0.97	
Obese ≥30	3	6100	1.68 (1.48 to 1.89)	0	0.92	Higher risk	0.63 (0.43 to 0.93)	0	0.62	Lower risk
Overall	5	11 688	1.78 (1.48 to 2.13)	0	0.37	Higher risk	0.71 (0.48 to 1.04)	42.13	0.15	
LGA:										
Underweight <18.5	5	38 837	0.64 (0.36 to 1.14)	78.1	0		2.47 (2.18 to 2.79)	0	0.65	Higher risk
Normal weight 18.5-24.9	9	362 060	0.69 (0.60 to 0.79)	69.47	0	Lower risk	1.91 (1.59 to 2.30)	89.16	0	Higher risk
Overweight 25-29.9	6	145 494	0.65 (0.61 to 0.70)	0	0.81	Lower risk	1.59 (1.30 to 1.96)	68.73	0	Higher risk
Obese ≥30	11	210 731	0.73 (0.65 to 0.81)	43.87	0.02	Lower risk	1.57 (1.46 to 1.68)	44.04	0.1	Higher risk
Overall	16	757 122	0.67 (0.61 to 0.74)	80.36	0	Lower risk	1.77 (1.62 to 1.94)	91.04	0	Higher risk
Macrosomia:										
Underweight <18.5	3	4452	0.66 (0.19 to 2.32)	0			2.31 (0.52 to 10.27)	0	0.52	
Normal weight 18.5-24.9	6	28 352	0.59 (0.33 to 1.06)	41.6	0.13		2.07 (1.87 to 2.30)	0	0.67	Higher risk
Overweight 25-29.9	4	6023	0.75 (0.43 to 1.29)	0	0.72		1.49 (1.25 to 1.77)	0	0.88	Higher risk
Obese ≥30	6	40 123	0.66 (0.57 to 0.77)	0	0.2	Lower risk	1.57 (1.50 to 1.64)	0	0.94	Higher risk
Overall	8	78 950	0.68 (0.58 to 0.80)	17.47	0.24	Lower risk	1.78 (1.60 to 1.99)	44.6	0.02	Higher risk
NICU:										
Normal weight 18.5-24.9	1	208	0.80 (0.39 to 1.65)	0			1.06 (0.41 to 2.74)	0		
Overweight 25-29.9	1	259	1.40 (0.73 to 2.69)	0			1.35 (0.73 to 2.50)	0		
Obese ≥30	4	19 142	0.89 (0.67 to 1.19)	0	0.43		1.23 (0.81 to 1.86)	11.53	0.2	
Overall	4	19 609	0.91 (0.75 to 1.09)	0	0.46		1.26 (1.09 to 1.45)	0	0.44	Higher risk
RDS:										
Normal weight 18.5-24.9	2	780	1.51 (0.57 to 3.99)	0			1.48 (0.67 to 3.24)	0	0.92	
Overweight 25-29.9	1	259	1.16 (0.42 to 3.20)	0			1.06 (0.40 to 2.81)	0		
Obese ≥30	1	213	1.20 (0.38 to 3.79)	0			0.91 (0.29 to 2.83)	0		
Overall	2	1252	1.29 (1.01 to 1.63)	0	0.98	Higher risk	1.10 (0.78 to 1.56)	0	0.95	
Hyperbilirubinaemia:										
Normal weight 18.5-24.9	2	780	1.01 (0.00 to 267.14)	1.9	0.31		1.57 (0.01 to 173.73)	0	0.43	
Overweight 25-29.9	1	259	0.89 (0.38 to 2.06)	0			1.03 (0.48 to 2.21)	0		
Obese ≥30	1	213	0.78 (0.29 to 2.12)	0			0.32 (0.10 to 1.04)	0		
Overall	2	1252	0.90 (0.53 to 1.51)	0	0.76		0.93 (0.28 to 3.14)	38	0.17	

CI=confidence interval; HDP=hypertensive disorders of pregnancy; LGA=large for gestational age; NICU=neonatal intensive care unit; SGA=small for gestational age; RDS=respiratory distress syndrome.
*P value for heterogeneity (Q test).

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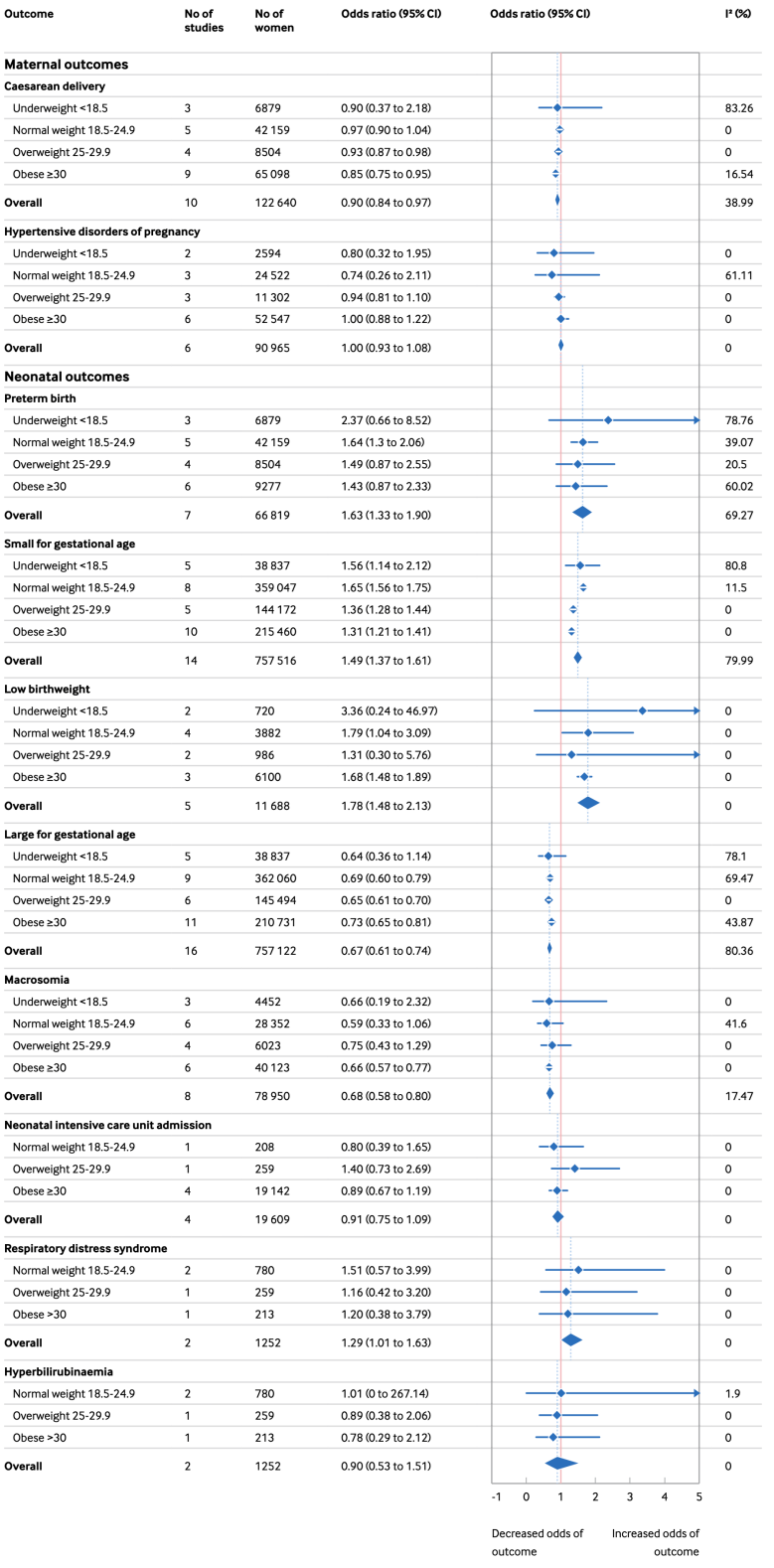
WHO BMI categories: below recommended GWG

Pooled odds ratios for studies using WHO BMI categories for maternal and neonatal outcomes (GWG below recommended)



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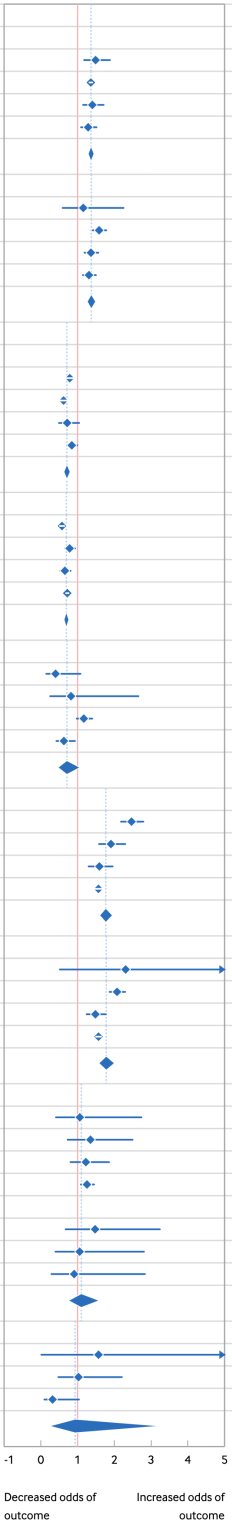
BMI=body mass index; GWG=gestational weight gain

Fig 3 | Pooled odds ratios for studies using WHO body mass index categories for maternal and neonatal outcomes (gestational weight gain below recommended). An interactive version of this graphic and downloadable data are available at https://public.flourish.studio/visualisation/25702892/

WHO BMI categories: above recommended GWG

Pooled odds ratios for studies using WHO BMI categories for maternal and neonatal outcomes (GWG above recommended)

Outcome	No of studies	No of women	Odds ratio (95% CI)	I² (%)
Maternal outcomes				
Caesarean delivery				
Underweight <18.5	3	6879	1.49 (1.18 to 1.88)	0
Normal weight 18.5-24.9	5	42 159	1.36 (1.32 to 1.40)	0
Overweight 25-29.9	4	8504	1.40 (1.15 to 1.71)	0
Obese ≥30	9	65 098	1.29 (1.09 to 1.52)	54.38
Overall	10	122 640	1.37 (1.30 to 1.44)	17.82
Hypertensive disorders of pregnancy				
Underweight <18.5	2	2594	1.16 (0.59 to 2.25)	0
Normal weight 18.5-24.9	3	24 522	1.59 (1.41 to 1.78)	0
Overweight 25-29.9	3	11 302	1.36 (1.19 to 1.56)	0
Obese ≥30	6	52 547	1.31 (1.14 to 1.50)	43.78
Overall	6	90 965	1.37 (1.28 to 1.48)	40.2
Neonatal outcomes				
Preterm birth				
Underweight <18.5	3	6879	0.79 (0.68 to 0.91)	0
Normal weight 18.5-24.9	5	42 159	0.62 (0.52 to 0.73)	14.88
Overweight 25-29.9	4	8504	0.72 (0.49 to 1.04)	20.93
Obese ≥30	6	9277	0.84 (0.72 to 0.99)	0
Overall	7	66 819	0.71 (0.64 to 0.79)	22.45
Small for gestational age				
Underweight <18.5	5	38 837	0.58 (0.52 to 0.64)	3.9
Normal weight 18.5-24.9	8	359 047	0.78 (0.66 to 0.93)	82.18
Overweight 25-29.9	5	144 172	0.66 (0.53 to 0.81)	30.54
Obese ≥30	10	215 460	0.72 (0.69 to 0.76)	0
Overall	14	757 516	0.69 (0.64 to 0.75)	83.16
Low birthweight				
Underweight <18.5	2	720	0.40 (0.15 to 1.08)	0
Normal weight 18.5-24.9	4	3882	0.82 (0.25 to 2.66)	61.57
Overweight 25-29.9	2	986	1.17 (0.98 to 1.40)	0
Obese ≥30	3	6100	0.63 (0.43 to 0.93)	0
Overall	5	11 688	0.71 (0.48 to 1.04)	42.13
Large for gestational age				
Underweight <18.5	5	38 837	2.47 (2.18 to 2.79)	0
Normal weight 18.5-24.9	9	362 060	1.91 (1.59 to 2.30)	89.16
Overweight 25-29.9	6	145 494	1.59 (1.30 to 1.96)	68.73
Obese ≥30	11	210 731	1.57 (1.46 to 1.68)	44.04
Overall	16	757 122	1.77 (1.62 to 1.94)	91.04
Macrosomia				
Underweight <18.5	3	4452	2.31 (0.52 to 10.27)	0
Normal weight 18.5-24.9	6	28 352	2.07 (1.87 to 2.30)	0
Overweight 25-29.9	4	6023	1.49 (1.25 to 1.77)	0
Obese ≥30	6	40 123	1.57 (1.50 to 1.64)	0
Overall	8	78 950	1.78 (1.60 to 1.99)	44.6
Neonatal intensive care unit admission				
Normal weight 18.5-24.9	1	208	1.06 (0.41 to 2.74)	0
Overweight 25-29.9	1	259	1.35 (0.73 to 2.50)	0
Obese ≥30	4	19 142	1.23 (0.81 to 1.86)	11.53
Overall	4	19 609	1.26 (1.09 to 1.45)	0
Respiratory distress syndrome				
Normal weight 18.5-24.9	2	780	1.48 (0.67 to 3.24)	0
Overweight 25-29.9	1	259	1.06 (0.40 to 2.81)	0
Obese ≥30	1	213	0.91 (0.29 to 2.83)	0
Overall	2	1252	1.10 (0.78 to 1.56)	0
Hyperbilirubinaemia				
Normal weight 18.5-24.9	2	780	1.57 (0.01 to 173.73)	0
Overweight 25-29.9	1	259	1.03 (0.48 to 2.21)	0
Obese ≥30	1	213	0.32 (0.10 to 1.04)	0
Overall	2	1252	0.93 (0.28 to 3.14)	38



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BMI=body mass index; GWG=gestational weight gain

Fig 4 | Pooled odds ratios for studies using WHO body mass index categories for maternal and neonatal outcomes (gestational weight gain above recommended). An interactive version of this graphic and downloadable data are available at https://public.flourish.studio/visualisation/25739784/

Table 5 | Summary of outcomes by Asian body mass index categories for gestational weight gain below or above recommended

Outcome	No of studies	No of women	GWG below recommended				GWG above recommended			
			OR (95% CI)	I^2 (%)	P value*	Direction	OR (95% CI)	I^2 (%)	P value*	Direction
Maternal outcomes										
Caesarean delivery:										
Underweight	2	4137	0.960 (0.53 to 1.74)	0	0.58		1.44 (0.81 to 2.58)	0	0.52	
Normal weight	3	24 178	0.98 (0.74 to 1.31)	0	0.62		1.38 (1.21 to 1.57)	0	0.32	Higher risk
Overweight + obese	3	9751	0.78 (0.40 to 1.52)	0	0.59		1.27 (0.99 to 1.62)	0	0.26	
Overall	3	38 066	0.97 (0.91 to 1.03)	0	0.84		1.37 (1.29 to 1.46)	0	0.37	Higher risk
HDP:										
Underweight	2	5115	3.09 (1.08 to 8.83)	0	0.77		1.09 (0.00 to 7.58×10^{7})	90.81	0	
Normal weight	3	25 177	6.61 (0.00 to 17291.43)	85.25	0.01		1.99 (0.02 to 203.07)	96.4	0	
Overweight + obese	3	5868	1.59 (1.10 to 2.30)	0		Higher risk	1.48 (0.49 to 4.44)	0	0.49	
Overall	3	36 160	3.58 (1.37 to 9.39)	84.45	0	Higher risk	1.66 (0.47 to 5.86)	94.6	0.94	
Neonatal outcomes										
Preterm birth:										
Underweight	2	4137	1.85 (0.28 to 12.07)	0	0.5		0.54 (0.00 to 385.94)	47	0.17	
Normal weight	2	22 941	2.09 (0.02 to 287.3)	72.85	0.05		0.58 (0.31 to 1.09)	0	0.58	
Overweight + obese	2	8488	1.32 (0.00 to 543.78)	9.23	0.29		2.20 (0.00 to 2.79×10^{8})	95.63	0	
Overall	2	35 566	1.69 (1.25 to 2.30)	8.96	0.32	Higher risk	0.79 (0.22 to 2.82)	95.18	0	
SGA:										
Underweight	2	4137	1.99 (0.00 to 3467.85)	82.91	0.02		0.50 (0.39 to 0.64)	0	0.86	
Normal weight	2	22 941	2.26 (0.01 to 1109)	83.93	0.01		0.66 (0.53 to 0.81)	0	0.75	Lower risk
Overweight + obese	2	8488	0.90 (0.68 to 1.19)	0	0.95		0.71 (0.44 to 1.15)	6.03	0.53	
Overall	2	35 566	1.67 (0.86 to 3.24)	87.38	0.01		0.62 (0.53 to 0.74)	41.22	0.29	Lower risk
Low birth weight:										
Underweight	2	14 327	2.29 (0.24 to 22.19)	15.69	0.28		0.31 (0.18 to 0.56)	0	0.70	Lower risk
Normal weight	2	62 219	2.42 (0.00 to 14084.82)	91.16	0		0.46 (0.25 to 0.87)	0	0.4	Lower risk
Overweight + obese	2	5221	0.70 (0.46 to 1.09)	0			0.53 (0.40 to 0.71)	0		Lower risk
Overall	2	81 767	1.91 (0.73 to 5.04)	95.74	0		0.44 (0.31 to 0.60)	68.98	0.03	Lower risk
LGA:										
Underweight	2	4137	0.76 (0.42 to 1.36)	0			2.07 (0.07 to 60.77)	48.29	0.16	
Normal weight	3	24 178	0.79 (0.38 to 1.66)	0	0.55		1.97 (1.52 to 2.56)	2.13	0.25	Higher risk
Overweight + obese	3	9287	0.94 (0.53 to 1.69)	0	0.84		1.44 (0.91 to 2.28)	45.57	0.15	
Overall	3	37 602	0.80 (0.72 to 0.89)	0	0.96		1.76 (1.42 to 2.18)	60.08	0.03	Higher risk
Macrosomia:										
Underweight	3	18 059	1.22 (0.00 to 2371.53)	92.7	0		0.84 (0 to 251000)	92.7	0	
Normal weight	3	84 106	1.05 (0.49 to 2.23)	86.2	0		1.47 (0.10 to 21.06)	86.2	0	
Overweight + obese	3	13 575	0.71 (0.45 to 1.11)	0	0.74		1.02 (0.23 to 4.55)	0	0	
Overall	3	115 740	1.01 (0.68 to 1.50)	88.9	0		1.11 (0.53 to 2.3)	88.9	0	

CI=confidence interval; HDP=hypertensive disorders of pregnancy; LGA=large for gestational age; SGA=small for gestational age.
*P value for heterogeneity (Q test).

BMI categories, GWG below the recommended range was associated with a lower risk of caesarean delivery across combined BMI categories (odds ratio 0.90, 95% confidence interval (CI) 0.84 to 0.97; I^2=39%; 10 studies; n=122 640) and within the overweight (0.93, 0.87 to 0.98; I^2=0%; 4 studies; n=8504) and obese (0.85, 0.75 to 0.95; I^2=17%; 9 studies; n=65 098) BMI groups. GWG above recommendations was associated with a higher risk of caesarean delivery across the combined BMI categories (odds ratio 1.37, 95% CI 1.30 to 1.44; I^2=18%; 10 studies; n=122 640); this effect was also apparent within all individual BMI groups (table 4). By Asian BMI categories, GWG below the recommended range was not associated with caesarean delivery across the combined BMI categories, whereas GWG above the range was associated with a higher risk of caesarean delivery (odds ratio 1.37, 95% CI 1.29 to 1.46; I^2=0%; 3 studies; n=38 066), an association seen only within the normal weight BMI group (1.38, 1.21 to 1.57; I^2=0%; 3 studies; n=24 178) (table 5).

Hypertensive disorders of pregnancy

Nine studies (n=127 125) assessed hypertensive disorders of pregnancy.[25 27 40 43 45 62 64 67 68] By WHO BMI categories, GWG below the recommended range was not associated with hypertensive disorders of pregnancy across the combined BMI categories or within BMI groups, whereas GWG above the range was associated with a higher risk of hypertensive disorders of pregnancy (odds ratio 1.37, 95% CI 1.28 to 1.48; I^2=40%; 6 studies; n=90 965). This effect was seen in all BMI groups except the underweight group (table 4). For Asian BMI categories, GWG below the recommended range was associated with a higher risk of hypertensive disorders of pregnancy across all BMI categories (odds ratio 3.58, 95% CI 1.37 to 9.39; I^2=84%; 3 studies; n=36 160). In the Asian studies, associations between GWG above the recommended range and hypertensive disorders of pregnancy were not significant across combined BMI categories or within individual BMI groups (table 5).

Neonatal outcomes

Preterm birth

Preterm birth was assessed in eight studies (n=68 412).[32 58 62-64 67 68 70] In studies using WHO BMI categories, GWG below recommendations was associated with a higher risk of preterm birth across all BMI categories (odds ratio 1.63, 95% CI 1.33 to 1.90; I^2=69%; 7 studies; n=66 819). Within BMI categories, this association was seen only in the normal weight group (table 4). GWG above the recommended range was associated with a lower risk of preterm birth overall (odds ratio 0.71, 95% CI 0.64 to 0.79; I^2=22%; 7 studies; n=66 819), and this was consistent within all except the overweight BMI group (table 4). Similarly, when Asian BMI categories were used, GWG below the recommended range was associated with a higher risk of preterm birth (odds ratio 1.69, 95% CI 1.25 to 2.30; I^2=9%; 2 studies; n=35 566), but this was not significant within individual BMI groups. We found no associations for GWG above recommendations with preterm birth (table 5).

Small for gestational age infants

Fifteen studies (n=793 082) assessed small for gestational age infants.[26 32 34 45 47 53 57 58 61-64 67 68 70] In studies using WHO BMI categories, GWG below the recommended range was associated with a higher risk of a small for gestational age infant across BMI categories (odds ratio 1.49, 95% CI 1.37 to 1.61; I^2=80%; 14 studies; n=757 516) and within each BMI group. GWG above the range was associated with a lower risk of a small for gestational age infant across BMI categories (odds ratio 0.69, 95% CI 0.64 to 0.75; I^2=83%; 14 studies; n=757 516), and within each BMI group (table 4). We found no association between GWG below recommendations and risk of a small for gestational age infant when Asian BMI categories were used, but GWG above recommendations was associated with a lower risk of a small for gestational age infant across all BMI categories (odds ratio 0.62, 95% CI 0.53 to 0.74; I^2=41%; 2 studies; n=35 566) and within the underweight and normal weight BMI groups (table 5).

Low birth weight

Seven studies (n=93 455) assessed low birth weight.[32 44 54 57 62 64 67] In studies using WHO BMI categories, GWG below the recommended range was associated with a higher risk of low birth weight across combined BMI categories (odds ratio 1.78, 95% CI 1.48 to 2.13; I^2=0%; 5 studies; n=11 688); within BMI groups, this was the case for normal weight and obese BMI groups only. We found no association between low birth weight and GWG above the recommended range for the combined categories, although a significant association existed within the obese BMI group (table 4). For Asian BMI categories, GWG below the recommended range was not associated with low birth weight, whereas GWG above the range was associated with a lower risk across all BMI categories (odds ratio 0.44, 95% CI 0.31 to 0.60; I^2=69%; 2 studies; n=81 767) and within each individual BMI group (table 5).

Large for gestational age infants

Seventeen studies (n=760 752) assessed large for gestational age infants.[25 26 32 34 45 47 53 57 58 61-63 66-68 70] In studies using WHO BMI categories, GWG below the recommended range was associated with a lower risk of a large for gestational age infant across combined BMI categories (odds ratio 0.67, 95% CI 0.61 to 0.74; I^2=80%; 16 studies; n=757 122) and within all BMI groups except the underweight group. GWG above the recommended range was associated with a higher risk of a large for gestational age infant across all BMI categories (odds ratio 1.77, 95% CI 1.62 to 1.94; I^2=91%; 16 studies; n=757 122) and within each individual BMI group (table 4). On the basis of Asian BMI categories, GWG below the recommended range was associated with a lower risk of a large for gestational age infant (odds ratio 0.80, 95% CI 0.72 to 0.89; I^2=0%; 3 studies; n=37 602), and GWG above recommended was associated a higher risk of a large for gestational age infant (odds ratio 1.76, 95% CI 1.42 to 2.18; I^2=60%; 3 studies; n=37 602) (table 5).

Macrosomia

Macrosomia was assessed in 10 studies (n=60 718).[26 32 44 54 57 62 63 67 68 70] By WHO BMI categories, GWG below the recommended range was associated with a lower risk of macrosomia across combined BMI categories (odds ratio 0.68, 95% CI 0.58 to 0.80; I^2=17%; 8 studies; n=78 950); this was consistent across all individual groups except the obese BMI group. GWG above the range was associated with a higher risk of macrosomia across combined BMI categories (odds ratio 1.78, 95% CI 1.60 to 1.99; I^2=45%; 8 studies; n=78 950); this was consistent within all except the underweight BMI group (table 4). We found no associations between GWG below or above recommended ranges and macrosomia across combined Asian BMI categories, including within individual groups (table 5).

Birth weight

Three studies assessed birth weight (n=3823),[30 55 63] two of which used WHO BMI categories. By WHO BMI categories, GWG below the recommended range was associated with lower birth weight across combined BMI categories (mean difference −184.54, 95% CI −278.03 to −91.06; I^2=59%; 2 studies; n=3089) (supplementary file 5), but not within individual BMI groups. GWG above the range was associated with higher birth weight (mean difference 118.33, 95% CI 53.80 to 182.85; I^2=28%; 2 studies; n=3089), but only within the obese BMI group. We could not assess Asian BMI categories as only one study examined this outcome.[27]

Neonatal intensive care unit admission

Four studies (n=19 609) assessed NICU admission,[25 45 63 68] all using WHO BMI categories. We found

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Table 6 | Summary of outcomes by obesity class for gestational weight loss and gestational weight gain (GWG) below recommended and above recommended

Outcome	No of studies	No of women	Gestational weight loss				GWG below recommended				GWG above recommended			
			OR (95% CI)	I^2 (%)	P value*	Direction	OR (95% CI)	I^2 (%)	P value*	Direction	OR (95% CI)	I^2 (%)	P value*	Direction
Maternal outcomes														
Caesarean delivery:														
Class I	2	37 250	0.74 (0.09 to 6.37)	55.46			0.82 (0.56 to 1.20)	0	0.83		1.46 (0.38 to 5.53)	88.73	0	
Class II	3	18 014	0.94 (0.56 to 1.56)	41.8	0.07		0.83 (0.60 to 1.15)	28.85	0.22		1.37 (1.25 to 1.51)	0	0.82	Higher risk
Class III	2	5449	0.67 (0.03 to 13.71)	75.84			0.79 (0.61 to 1.02)	0	0.56		1.27 (0.38 to 4.19)	27.79	0.24	
Overall	3	60 713	0.79 (0.62 to 1.01)	64.19	0.28		0.82 (0.76 to 0.88)	0	0.62	Lower risk	1.38 (1.26 to 1.52)	55.3	0.03	Higher risk
HDP:														
Class I	1	21 626	NA				0.83 (0.68 to 1.02)				1.54 (1.34 to 1.76)			Higher risk
Class II	1	15 040	NA				0.86 (0.08 to 9.70)	83.35	0.01		1.22 (0.22 to 6.9)	72.24	0.06	
Class III	N/A	5798	NA				0.73 (0.57 to 0.93)			Lower risk	1.38 (1.11 to 1.72)			Higher risk
Overall	N/A	42 464	NA				0.82 (0.62 to 1.09)	60.9	0.05		1.35 (1.05 to 1.73)	64.64	0.04	Higher risk
Neonatal outcomes														
SGA:														
Class I	3	68 918	1.65 (1.54 to 1.78)	0		Higher risk	1.15 (0.77 to 1.72)	67.06	0.21		0.65 (0.61 to 0.69)	0	0.89	Lower risk
Class II	4	29 724	4.86 (0.21 to 111.36)	98.55	0.01		1.32 (1.19 to 1.45)	0	0.42	Higher risk	0.80 (0.63 to 1.01)	0	0.35	
Class III	3	11 463	1.57 (0.89 to 2.78)	0			1.43 (0.84 to 2.43)	0	0.38		0.95 (0.46 to 1.95)	40.17	0.19	
Overall	4	110 105	2.53 (1.03 to 6.23)	97.64	0.05	Higher risk	1.25 (1.12 to 1.40)	38.08	0.13	Higher risk	0.74 (0.65 to 0.86)	55.09	0.02	Lower risk
LGA:														
Class I	3	68 918	0.65 (0.32 to 1.35)	71.82	0.02		0.70 (0.47 to 1.04)	66.48	0		1.77 (1.35 to 2.33)	68.25	0.06	Higher risk
Class II	3	24 212	0.67 (0.57 to 0.79)	0	0.84	Lower risk	0.89 (0.38 to 2.08)	89.78	0		1.48 (1.27 to 1.73)	0	0.53	Higher risk
Class III	3	11 463	0.50 (0.26 to 0.98)	58.48	0.08	Lower risk	0.68 (0.59 to 0.78)	0	0.52	Lower risk	1.31 (0.89 to 1.93)	0	0.15	
Overall	3	104 593	0.61 (0.50 to 0.73)	57.05	0.02	Lower risk	0.75 (0.63 to 0.90)	79.93	0	Lower risk	1.54 (1.36 to 1.75)	78.29		Higher risk

CI=confidence interval; HDP=hypertensive disorders of pregnancy; LGA=large for gestational age; NA=not available; SGA=small for gestational age.
*P value for heterogeneity (Q test).

no association between GWG below the recommended range and NICU admission, whereas GWG above the range was associated with a higher risk of NICU admission across BMI categories (odds ratio 1.26, 95% CI 1.09 to 1.45; I^2=0; 4 studies; n=19 609) but not within individual BMI groups (table 4). No studies assessed this outcome for Asian BMI categories.

Respiratory distress syndrome

Two studies (n=1252) assessed respiratory distress syndrome,[32 68] both using WHO BMI categories. GWG below the recommended range was associated with a higher risk of respiratory distress syndrome across combined BMI categories (odds ratio 1.29, 95% CI 1.01 to 1.63; I^2=0; 2 studies; n=1252) but not within individual BMI groups, whereas GWG above the recommended range was not associated with respiratory distress across or within BMI groups (table 4).

Hyperbilirubinaemia

Two studies (n=1252) assessed hyperbilirubinaemia/neonatal jaundice, both using WHO BMI categories.[32 68] Neither GWG below nor above the recommended range was associated with neonatal jaundice (table 4).

Subgroup analysis

Obesity classes include class 1 (BMI 30-34.9), class 2 (BMI 35-39.9), and class 3 (BMI ≥40). Four studies specifically assessed outcomes stratified by these BMI classes (all using WHO BMI criteria)[26 45 61 64] and were included in a subgroup analysis (fig 7, fig 8, fig 9, table 6).

Across the four studies, 64% of women were in obesity class 1, 24% in class 2, and 12% in class 3. One study included only obesity class 2 and above.[64] Two studies classified GWG into four categories: weight loss and GWG below (0-5 kg), within (5-9 kg), and above (≥9 kg) recommended ranges.[26 61] One study used multiple weight categories: weight loss (−2 kg), stable weight (−2-2 kg), low GWG (0-5 kg), normal GWG (5-9.1 kg), and excessive (>9.1 kg).[45] Another study used different weight categories: weight loss, no change, 1-10 lb (0.45-4.5 kg), normal GWG, 21-40 lb (9.5-18 kg), and 51 lb (22.7 kg) or more.[64] Only one study each assessed preterm birth, low birth weight, and gestational diabetes mellitus,[64] macrosomia,[26] or NICU,[45] precluding meta-analysis.

For the meta-analysis, four GWG groups existed: weight loss and GWG below (0-5 kg), within (5-9 kg), and above (>9 kg) recommended ranges. Weight loss was associated with a lower risk of a large for gestational age infant (odds ratio 0.61, 95% CI 0.50 to 0.73; I^2=57%; 3 studies; n=104 593) (with class 3 obesity associated with the greatest risk reduction) and a higher risk of a small for gestational age infant (2.53, 1.03 to 6.23; I^2=98%; 4 studies; n=110 105), with no association with caesarean delivery (table 6). Weight gain below the recommended range was associated with a higher risk of a small for gestational age infant (odds ratio 1.25, 95% CI 1.12 to 1.40; I^2=38%; 4 studies; n=110 105) and a lower risk of a large for gestational age infant (0.75, 0.63 to 0.90; I^2=83%; 3 studies; n=104 593) and caesarean delivery (0.82, 0.76 to 0.88; I^2=0%; 3 studies; n=60 713); we found no association with hypertensive disorders of pregnancy (table 6). GWG above the range was associated with a lower risk of a small for gestational age infant (odds ratio 0.74, 95% CI 0.65 to 0.86; I^2=55%; 4 studies; n=110 105) (fig 9, table 6) and a higher risk of a large for gestational age infant (1.54, 1.36 to 1.75), caesarean delivery (1.38, 1.26 to 1.52), and hypertensive disorders of pregnancy (1.35, 1.05 to 1.73). Women with class 1 obesity had greater risk than women in other obesity classes for hypertensive disorders of pregnancy and large for gestational age infants (table 6).

Publication bias

On the basis of funnel plots and Egger's tests, we found no evidence of publication bias for studies using WHO BMI categories for outcomes of caesarean delivery, hypertensive disorders of pregnancy, preterm birth, small/large for gestational age infants, low birth weight, and macrosomia (supplementary figure F). We did not assess publication bias for NICU admissions, birth weight, respiratory distress syndrome, or neonatal jaundice or for studies using Asian BMI categories (all had fewer than five studies).

Sensitivity analysis

Sensitivity analyses were consistent with the main findings for all outcomes except NICU admission, for which GWG above guidelines was no longer associated with an increased risk (odds ratio 1.19, 95% CI 0.84 to 1.69) (supplementary file 6). Additional sensitivity analyses excluding studies assessed as being at high risk of bias[32 62] (supplementary file 7) or comparing studies by crude versus adjusted odds ratios (supplementary file 8) did not materially alter the results, although these analyses were not possible for all outcomes owing to the small number of studies.

Descriptive analysis

Outcomes not included in meta-analysis

Eight studies assessed gestational diabetes mellitus[27 40 56 62-64 67 70]; however, these studies used variable definitions and populations, with some including pre-gestational diabetes, precluding meta-analysis. Li and colleagues defined gestational diabetes mellitus as women with impaired glucose tolerance and diabetes according to WHO criteria, with GWG above the recommended range being associated with a lower risk of gestational diabetes mellitus in all groups except those with obesity.[70] Miao and colleagues used International Association for Diabetes in Pregnancy Study Group (IADPSG) criteria in their study[56]; women with gestational diabetes mellitus gained less weight than women without gestational diabetes mellitus. Asvanarunat and colleagues used the White classification for gestational diabetes mellitus at any onset in pregnancy, finding that GWG below

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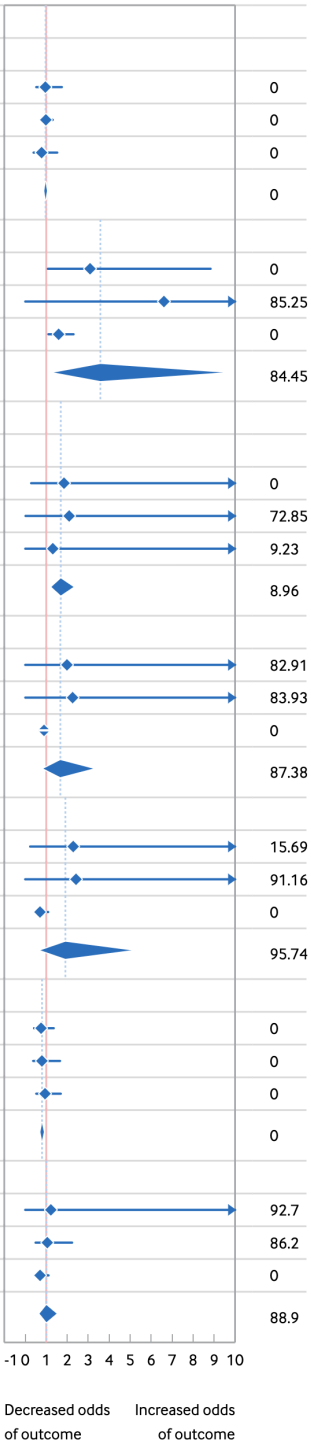
Asian BMI categories: below recommended GWG

Pooled odds ratios for studies using Asian BMI categories for maternal and neonatal outcomes (GWG below recommended)

Outcome	No of studies	No of women	Odds ratio (95% CI)	I² (%)
Maternal outcomes				
Caesarean delivery				
Underweight	2	4137	0.96 (0.53 to 1.74)	0
Normal weight	3	24 178	0.98 (0.74 to 1.31)	0
Overweight + obese	3	9751	0.78 (0.40 to 1.52)	0
Overall	3	38 066	0.97 (0.91 to 1.03)	0
Hypertensive disorders of pregnancy				
Underweight	2	5115	3.09 (1.08 to 8.83)	0
Normal weight	3	25 177	6.61 (0 to 17291.43)	85.25
Overweight + obese	3	5868	1.59 (1.10 to 2.30)	0
Overall	3	36 160	3.58 (1.37 to 9.39)	84.45
Neonatal outcomes				
Preterm birth				
Underweight	2	4137	1.85 (0.28 to 12.07)	0
Normal weight	2	22 941	2.09 (0.02 to 287.3)	72.85
Overweight + obese	2	8488	1.32 (0 to 543.78)	9.23
Overall	2	35 566	1.69 (1.25 to 2.30)	8.96
Small for gestational age				
Underweight	2	4137	1.99 (0 to 3467.85)	82.91
Normal weight	2	22 941	2.26 (0.01 to 1109)	83.93
Overweight + obese	2	8488	0.90 (0.68 to 1.19)	0
Overall	2	35 566	1.67 (0.86 to 3.24)	87.38
Low birthweight				
Underweight	2	14 327	2.29 (0.24 to 22.19)	15.69
Normal weight	2	62 219	2.42 (0 to 14084.82)	91.16
Overweight + obese	2	5221	0.70 (0.46 to 1.09)	0
Overall	2	81 767	1.91 (0.73 to 5.04)	95.74
Large for gestational age				
Underweight	2	4137	0.76 (0.42 to 1.36)	0
Normal weight	3	24 178	0.79 (0.38 to 1.66)	0
Overweight + obese	3	9287	0.94 (0.53 to 1.69)	0
Overall	3	37 602	0.80 (0.72 to 0.89)	0
Macrosomia				
Underweight	3	18 059	1.22 (0 to 2371.53)	92.7
Normal weight	3	84 106	1.05 (0.49 to 2.23)	86.2
Overweight + obese	3	13 575	0.71 (0.45 to 1.11)	0
Overall	3	115 740	1.01 (0.68 to 1.50)	88.9



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BMI=body mass index; GWG=gestational weight gain

Fig 5 | Pooled odds ratios for studies using Asian body mass index categories for maternal and neonatal outcomes (gestational weight gain below recommended). An interactive version of this graphic and downloadable data are available at https://public.flourish.studio/visualisation/25740288/

Asian BMI categories: above recommended GWG

Pooled odds ratios for studies using Asian BMI categories for maternal and neonatal outcomes (GWG above recommended)

Outcome	No of studies	No of women	Odds ratio (95% CI)	I² (%)
Maternal outcomes				
Caesarean delivery				
Underweight	2	4137	1.44 (0.81 to 2.58)	0
Normal weight	3	24 178	1.38 (1.21 to 1.57)	0
Overweight + obese	3	9751	1.27 (0.99 to 1.62)	0
Overall	3	38 066	1.37 (1.29 to 1.46)	0
Hypertensive disorders of pregnancy				
Underweight	2	5115	1.09 (0 to 75 800 000)	90.81
Normal weight	3	25 177	1.99 (0.02 to 203.07)	96.4
Overweight + obese	3	5868	1.48 (0.49 to 4.44)	0
Overall	3	36 160	1.66 (0.47 to 5.86)	94.6
Neonatal outcomes				
Preterm birth				
Underweight	2	4137	0.54 (0 to 385.94)	47
Normal weight	2	22 941	0.58 (0.31 to 1.09)	0
Overweight + obese	2	8488	2.20 (0 to 279 000 000)	95.63
Overall	2	35 566	0.79 (0.22 to 2.82)	95.18
Small for gestational age				
Underweight	2	4137	0.50 (0.39 to 0.64)	0
Normal weight	2	22 941	0.66 (0.53 to 0.81)	0
Overweight + obese	2	8488	0.71 (0.44 to 1.15)	6.03
Overall	2	35 566	0.62 (0.53 to 0.74)	41.22
Low birthweight				
Underweight	2	14 327	0.31 (0.18 to 0.56)	0
Normal weight	2	62 219	0.46 (0.25 to 0.87)	0
Overweight + obese	2	5221	0.53 (0.40 to 0.71)	0
Overall	2	81 767	0.44 (0.31 to 0.60)	68.98
Large for gestational age				
Underweight	2	4137	2.07 (0.07 to 60.77)	48.29
Normal weight	3	24 178	1.97 (1.52 to 2.56)	2.13
Overweight + obese	3	9287	1.44 (0.91 to 2.28)	45.57
Overall	3	37, 602	1.76 (1.42 to 2.18)	60.08
Macrosomia				
Underweight	3	18 059	0.84 (0 to 251 000)	92.7
Normal weight	3	84 106	1.47 (0.10 to 21.06)	86.2
Overweight + obese	3	13 575	1.02 (0.23 to 4.55)	0
Overall	3	115 740	1.11 (0.53 to 2.30)	88.9

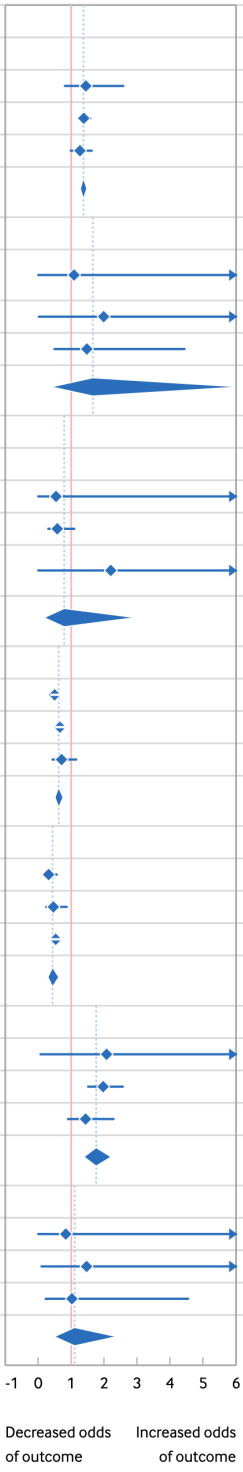

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Fig 6 | Pooled odds ratios for studies using Asian body mass index categories for maternal outcomes and outcomes (gestational weight gain above recommended). An interactive version of this graphic and downloadable data are available at https://public.flourish.studio/visualisation/25740464/

Obese BMI subroup: weight loss

Pooled odds ratios for studies using obese BMI subgroup analysis (weight loss)

Outcome	No of studies	No of women	Odds ratio (95% CI)	I² (%)
Maternal outcomes				
Caesarean delivery				
Class I	2	37 250	0.74 (0.09 to 6.37)	55.46
Class II	3	18 014	0.94 (0.56 to 1.56)	41.8
Class III	2	5449	0.67 (0.03 to 13.71)	75.84
Overall	3	60 713	0.79 (0.62 to 1.01)	64.19
Neonatal outcomes				
Small for gestational age				
Class I	3	68 918	1.65 (1.54 to 1.78)	0
Class II	4	29 724	4.86 (0.21 to 111.36)	98.55
Class III	3	11 463	1.57 (0.89 to 2.78)	0
Overall	4	110 105	2.53 (1.03 to 6.23)	97.64
Large for gestational age				
Class I	3	68 918	0.65 (0.32 to 1.35)	71.82
Class II	3	24 212	0.67 (0.57 to 0.79)	0
Class III	3	11 463	0.50 (0.26 to 0.98)	58.48
Overall	3	104 593	0.61 (0.50 to 0.73)	57.05

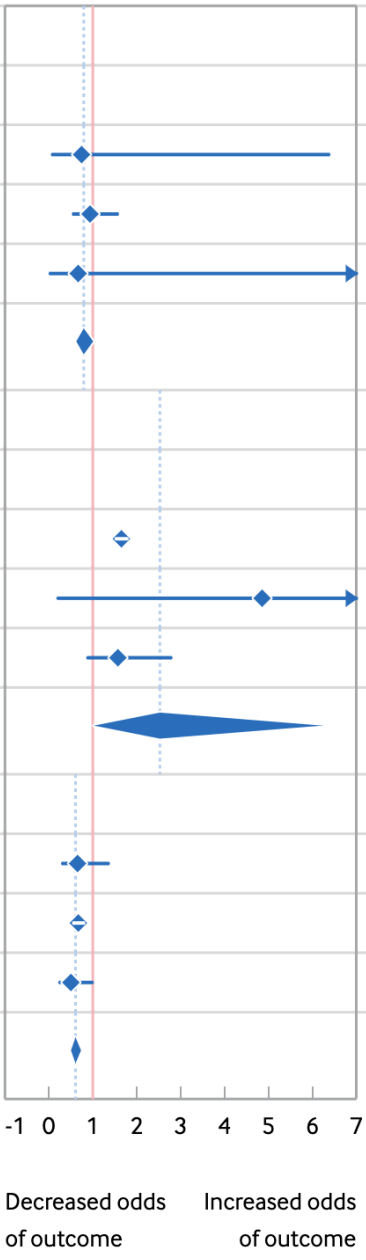

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Fig 7 | Pooled odds ratios for obese subgroup analysis (weight loss). An interactive version of this graphic and downloadable data are available at https://public.flourish.studio/visualisation/25740844/

Obese BMI subroup: weight gain below recommended

Pooled odds ratios for studies using obese BMI subgroup analysis (weight gain below recommended)

Outcome	No of studies	No of women	Odds ratio (95% CI)	I² (%)
Maternal outcomes				
Caesarean delivery				
Class I	2	37 250	0.82 (0.56 to 1.20)	0
Class II	3	18 014	0.83 (0.60 to 1.15)	28.85
Class III	2	5449	0.79 (0.61 to 1.02)	0
Overall	3	60 713	0.82 (0.76 to 0.88)	0
Hypertensive disorders of pregnancy				
Class I	1	21 626	0.83 (0.68 to 1.02)	0
Class II	1	15 040	0.86 (0.08 to 9.70)	83.35
Class III	2	5798	0.73 (0.57 to 0.93)	0
Overall	2	42 464	0.82 (0.62 to 1.09)	60.9
Neonatal outcomes				
Small for gestational age		68 918	1.15 (0.77 to 1.72)	67.06
Class I	3	29 724	1.32 (1.19 to 1.45)	0
Class II	4	11 463	1.43 (0.84 to 2.43)	0
Class III	3	110 105	1.25 (1.12 to 1.40)	38.08
Overall	4			
Large for gestational age		68 918	0.70 (0.47 to 1.04)	89.76
Class I	3	24 212	0.89 (0.38 to 2.08)	89.78
Class II	3	11 463	0.68 (0.59 to 0.78)	0
Class III	3	104 593	0.75 (0.63 to 0.90)	82.72
Overall	3	104 593	0.61 (0.50 to 0.73)	57.05

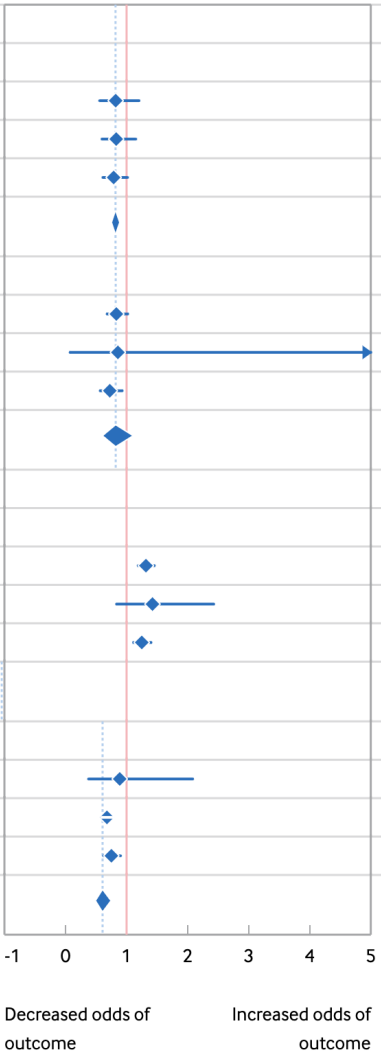

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Fig 8 | Pooled odds ratios for obese subgroup analysis (gestational weight gain below recommended). An interactive version of this graphic and downloadable data are available at https://public.flourish.studio/visualisation/25740972/

recommendations was associated with higher risk of gestational diabetes mellitus, except in the overweight group.[67] Gante and colleagues used either Carpenter and Coustan or IADPSG criteria in a cohort restricted to women with obesity and gestational diabetes mellitus and found that GWG <5 kg was associated with better obstetric and neonatal outcomes than adequate or excessive GWG.[63]

Four studies did not define gestational diabetes mellitus.[27 40 62 64] Deputy and colleagues included women with both pre-pregnancy diabetes and gestational diabetes mellitus (not defined) and reported that GWG below or above recommendations was associated with a higher or lower risk of gestational diabetes mellitus, respectively, in the normal weight and obese group but not in the underweight group.[40] The study by Class and colleagues was restricted to women with obesity, for whom GWG below guidelines was associated with a lower risk of gestational diabetes mellitus.[64] Guan and colleagues suggested

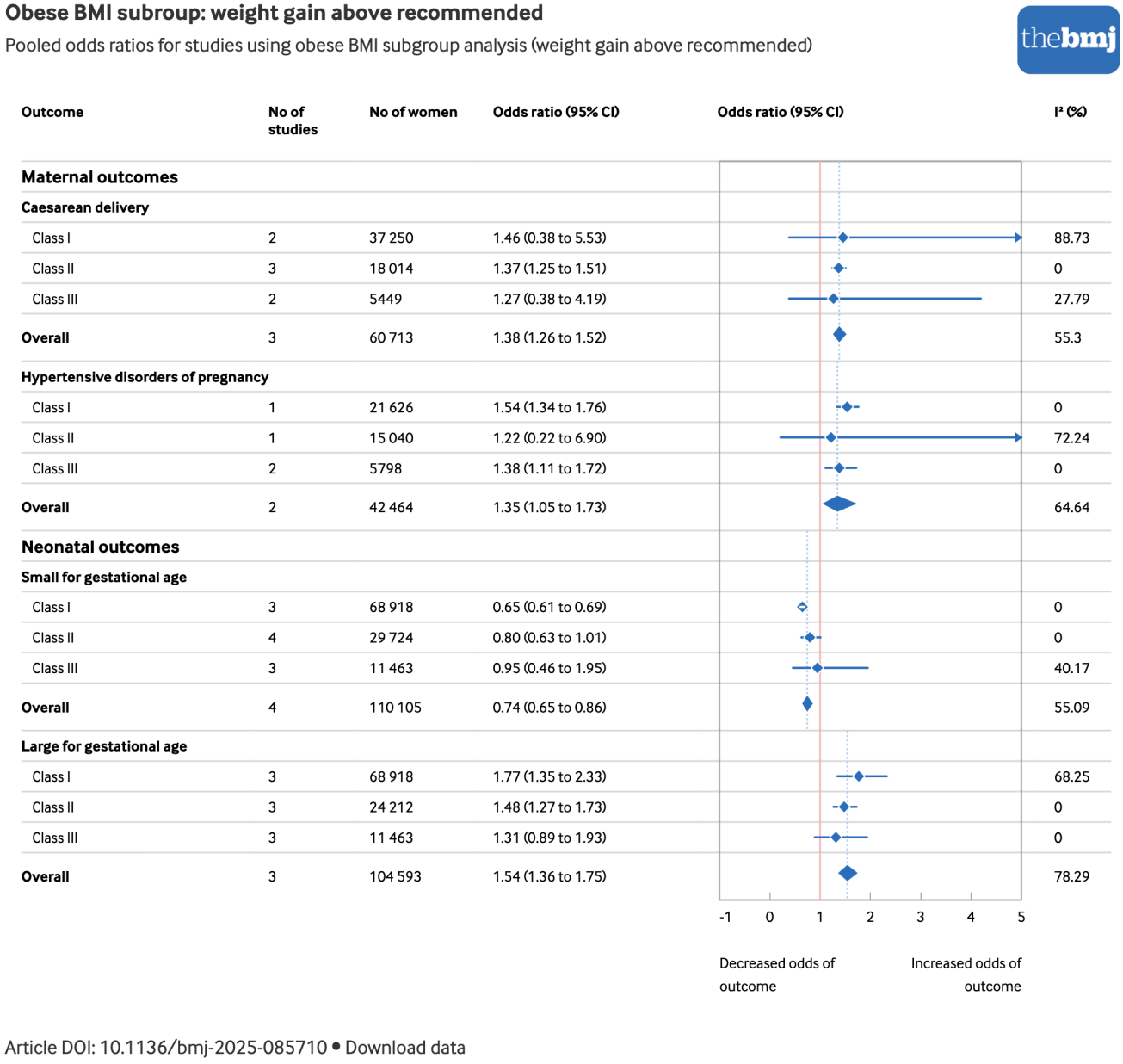

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Fig 9 | Pooled odds ratios for obese subgroup analysis (gestational weight gain above recommended). An interactive version of this graphic and downloadable data are available at https://public.flourish.studio/visualisation/25741159/

that inadequate GWG was associated with a higher risk of gestational diabetes mellitus in women with normal BMI and excess GWG was negatively associated with gestational diabetes mellitus in women with overweight BMI.[62] Somprasit and colleagues found that excess GWG was associated with a lower risk of gestational diabetes mellitus in women with elevated BMI, whereas no association between GWG and gestational diabetes mellitus was found among women with normal BMI.[27]

Studies not included in meta-analysis

Fifteen studies were included in the systematic review but not in the meta-analysis,[31 33 35 42 46 48-52 56 59 60 65 69] owing to any of five reasons: GWG within the recommended range in each BMI category was not used as the reference group; study specific GWG recommendations were used, which were not comparable with other studies; inconsistent definitions meant that outcomes were not amenable to meta-analysis (for example, amniotic fluid, neonatal length of stay, gestational diabetes mellitus); only a single study assessed the outcome of interest (for example, induction of labour,[27] prolonged second stage of labour[27]); and long term outcomes beyond the scope of this publication were assessed: childhood cognition tests,[60] childhood weight measurements,[33 49] attention-deficit hyperactivity disorder,[52] and

postpartum weight retention.[31] Details of these studies and their reported outcomes and summary results are provided in supplementary table A.

Discussion

Principal findings

Against the backdrop of increasing maternal obesity globally, this systematic review and meta-analysis captures 1.6 million pregnant women since 2009 from five of the six WHO world regions and includes studies in all languages. In this context, we provide contemporary evidence on diverse populations and broad maternal and neonatal outcomes associated with GWG across a spectrum of BMI and GWG categories. These findings close key evidence gaps and may inform the process of the WHO GWG Technical Advisory Group in defining eligibility criteria, determinants, and outcomes for the individual patient data sample that will underpin globally applicable GWG standards and optimal GWG ranges.

Around half (53%) of the overall sample had a normal pre-pregnancy BMI, and the remainder were classified as underweight (6%), overweight (19%), or obese (22%). Only a third (32%) had GWG within recommended ranges, with 23% gaining less and 45% gaining more than recommended. According to WHO BMI criteria, GWG below the IOM recommended range was associated with lower risk of caesarean delivery, a large for gestational age infant, and macrosomia but higher risk of preterm birth, a small for gestational age infant, low birth weight, and respiratory distress. Conversely, GWG above the IOM recommended range was associated with a higher birth weight and a higher risk of caesarean delivery, hypertensive disorders of pregnancy, a large for gestational age infant, macrosomia, and NICU admission (a new finding) and a lower risk of preterm birth and a small for gestational age infant. Similar patterns were apparent when Asian BMI categories were used in studies conducted in this world region, with GWG below recommended associated with a higher risk of hypertensive disorders of pregnancy and preterm birth and a lower risk of a large for gestational age infant, whereas GWG above recommendations was associated with a higher risk of caesarean delivery and a large for gestational age infant and a lower risk of a small for gestational age infant and low birth weight. A notable exception was the finding that insufficient weight gain was associated with a higher risk of hypertensive disorders of pregnancy in Asian studies.

Global burden of increasing BMI and GWG

Maternal BMI and GWG are increasing globally,[10] with known drivers including eco-social vulnerabilities such as ultra-processed food, lived environment, and socioeconomic status.[72] In our study across world regions, we have shown high pre-conception BMI in 41% of pregnancies and excess or inadequate GWG in 68% of pregnancies.[10 11 73 74-76] This is clinically significant on a global scale given that 130 million births occur annually,[77] reinforcing the worldwide health, system, and economic burden of GWG. Our group and others have reported clear associations between GWG and adverse pregnancy outcomes by BMI category in previous aggregate and individual patient data meta-analyses.[10 11 19 73 74] Here, we have demonstrated the international relevance of IOM GWG guidelines on the basis of associations between GWG and adverse outcomes. Furthermore, this is the first meta-analysis to identify additional clinical outcomes including neonatal effects such as the increased risk of respiratory distress syndrome associated with GWG below recommendations (albeit on the basis of two studies). We also showed an increased risk of NICU admissions with GWG above recommendations. Together, these findings definitively reinforce the need for recognition of the risks of GWG outside IOM recommendations. WHO is now developing global standards for healthy GWG, and implementation of effective strategies to optimise GWG has the potential to improve a broad range of maternal and neonatal outcomes internationally.

Regional differences in BMI and GWG

Controversy has persisted around the application of global WHO versus regional BMI categories when developing reference standards for healthy GWG, with evidence supporting lower BMI thresholds and variable GWG standards in Asian regions. We have captured five studies from Asia that used WHO BMI categories, and many studies from China applied regional BMI criteria, limiting generalisability across Asia. Results from this region showed wide confidence intervals, indicating uncertainty. Overall, distinguishing population specific risks from BMI classification differences in the region was difficult. This represents an important gap, as a previous systematic review reported that women from Korea and Taiwan have greater GWG and postpartum weight retention than women from other Asian countries.[78] Given that 60% of the global population reside in Asia, a better understanding of differences in BMI categories across regions and how these relate to variations in GWG related risk, is an important consideration for future research. This supports ongoing efforts to incorporate diverse populations across world regions and settings in developing globally relevant GWG standards.

Obesity subgroup analysis

We have extended previous analyses with obesity subgroup analyses, distinguishing between weight loss during pregnancy and GWG below guidelines (0-5 kg), to better understand respective risks, particularly for small for gestational age infants. Weight loss and weight gain below guidelines were both associated with an increased risk of small for gestational age infants and a decreased risk of large for gestational age infants. The relation between weight loss and small for gestational age infants remains inconsistent across the literature, with some reporting an increased risk,[10 75] unsupported by others.[76] GWG below the recommended range was associated with a lower risk

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of caesarean delivery; weight loss also showed a lower risk but did not reach statistical significance. GWG above recommendations was associated with a lower risk of small for gestational age infants but higher risks of large for gestational age infants, caesarean delivery, and hypertensive disorders of pregnancy. Women with class 1 obesity had a greater risk than other BMI classes for large for gestational age infants, which may be related to higher absolute GWG in those with lower BMI in the obese range or potentially to the larger sample size and power to detect differences within this obesity class. Overall, the safety and implications of weight loss in women with a BMI in the obese range during pregnancy remain uncertain, with further research needed across a broader range of outcomes.

Strengths and limitations of study

Strengths of this review include internationally endorsed methods, outcomes informed by the WHO GWG Technical Advisory Group, a protocol registered a priori, and comprehensive, systematic searches across multiple databases. The review provides contemporary, globally relevant evidence to inform the WHO global initiative on the development of GWG standards and is led by a highly experienced team, including members of the WHO GWG expert Technical Advisory Group (EB, MAS, MFU, CMM, HT). Our findings are based on data from 1.6 million women with strong international representation, representing five of the six WHO world regions. We provide evidence for a more extensive range of maternal and neonatal outcomes than previously reported and are the first to report associations of GWG below and above guidelines with respiratory distress syndrome and NICU admissions, respectively. We did sensitivity analyses to assess the robustness of the findings, particularly given the potential influence of small sample sizes, small study numbers, variable study quality, and between study heterogeneity. For studies using WHO BMI categories, the findings were consistent for all outcomes except NICU admissions, for which GWG above the recommended range was no longer associated with an increased risk; however, these results should be interpreted with caution given the small sample size. Our broad inclusion criteria and stratified approach account for different BMI classification systems (WHO and Asian categories) to provide region specific insights and ensure meaningful comparisons in the pooled analysis, and different GWG classifications are included in narrative synthesis. We also included non-English language studies to enhance global relevance and proactively sought missing information about eligibility (age >18; how final gestational weight was collected) through contact with authors. Studies were restricted to women aged ≥18 years, which reduces heterogeneity as adolescent girls have different physiological needs, growth patterns, and pregnancy risks compared with adult women and may have distinct GWG related risks that need separate assessment. Most (90%) studies were of high quality, and our findings provide critical evidence in support of WHO's efforts to optimise GWG and improve perinatal outcomes worldwide.

The study has some limitations. Heterogeneity in BMI and GWG classifications was evident and, although mitigated to some extent by separate analyses of WHO and Asian BMI categories, this prevented pooling for some of the studies owing to non-comparable GWG and/or BMI categorisations. We did not seek missing or unstratified outcome/exposure data from authors, but we considered them in risk of bias assessments and narrative synthesis, respectively. Despite the inclusion of all languages, studies from Southern Asian and African regions were notably absent, and few studies from low income countries met our inclusion criteria, limiting diversity. The restriction to studies of women aged ≥18 years resulted in the exclusion of some studies with a small percentage of adolescent participants, and limited author responses may have led to further exclusions. Some outcomes were reported in single studies, precluding meta-analysis, and meta-regression was not possible owing to data limitations (covariates such as smoking status, mean age, nulliparity, and ethnicity were not stratified by BMI and GWG). Lack of reporting of these key covariates also limited our ability to explore their potential confounding or effect modification. This may have contributed to the heterogeneity observed in some pooled outcomes and introduces the possibility of residual confounding. Some statistically significant odds ratios were modest in size (0.80-1.25), and their clinical relevance may vary depending on the context of each outcome, including baseline risk, severity, and potential impact.

Inconsistencies in outcome definitions also reduced comparability and may affect interpretation. This was particularly problematic for the outcome of gestational diabetes mellitus, which could not be assessed in meta-analysis owing to heterogeneity in populations and diagnostic criteria. Lifestyle modifications and medications after diagnosis of gestational diabetes mellitus may influence GWG,[79] and some women experience weight loss, potentially leading to reverse causation in the observed findings. Future studies may consider reporting of GWG at the time of diagnosis of gestational diabetes mellitus, rather than total GWG, as that may be more indicative of risk.[80] Findings related to hypertensive disorders of pregnancy were similarly complex, with differing relations with GWG depending on pre-pregnancy BMI. Interpreting this outcome is nuanced: greater GWG can increase the risk of hypertensive disorders of pregnancy, but women with hypertensive disorders of pregnancy experience oedema and weight gain unrelated to fat accumulation during pregnancy.[73] Because GWG can be both a cause and consequence of hypertensive disorders of pregnancy, distinguishing between the two mechanisms and the direction of association is challenging. Similarly, the association between lower GWG and preterm birth may reflect reverse causation, whereby shorter gestation limits the time available for weight gain, rather than low GWG contributing

to preterm birth. Moreover, preterm birth may be medically induced owing to complications, and this can vary across populations and local clinical protocols. NICU admissions are also influenced by multiple, interrelated factors with complex underlying mechanisms above and beyond GWG, which were not captured in this review. Finally, although corrections for multiple testing are not routinely applied in systematic reviews, we acknowledge that evaluating multiple outcomes can give rise to false positives, especially for subgroup and sensitivity analyses. Given these complexities and the inherent analytical limitations of the data, our findings should be interpreted with caution.

Comparison with other studies

Notably, results from individual patient data meta-analyses have been largely consistent with aggregate data meta-analyses, showing that inadequate GWG was associated with a higher risk of low birth weight,[81] small for gestational age infants,[81] and preterm birth,[71] whereas excess GWG was associated with a higher risk of hypertensive disorders of pregnancy,[71] large for gestational age infants,[71 81 82] and caesarean delivery[82] and lower risks of small for gestational age infants,[82] with inconsistent associations with preterm birth.[71 81 82] However, individual patient data meta-analyses to date have not fully captured real world GWG associations,[71 81-83] as they have been limited by underrepresentation of certain populations (for example, Asian populations), limited breadth of maternal and neonatal outcomes, reliance on self-reported or imputed weights (which are affected by biases and assumptions), and/or inclusion of data from randomised controlled trials in which participation can affect behaviour and subsequent risk. Here, we complement and extend the individual patient data evidence base by mapping the published evidence across regions and outcomes, helping to identify gaps and inform priorities for future individual patient data synthesis. Individual patient data meta-analysis is a major undertaking in cost, time, and labour, yet this review highlights the need for the WHO work based on robust individual patient data meta-analysis to overcome the limitations of previous such analyses, refine GWG standards, and strengthen global maternal health policy.

Conclusions

This large systematic review assesses broad outcomes across 1.6 million pregnancies, providing an important update to previous studies by including contemporary populations across five WHO world regions and a broad BMI range. We report high rates of excess maternal BMI and GWG outside recommended ranges and show that GWG greater than or less than IOM guideline recommendations was associated with higher risks of broad adverse maternal and neonatal outcomes, compared with GWG within recommendations, with new expanded associations noted for neonatal outcomes. Given the differences in BMI ranges applied to determine recommended GWG, especially across Asian regions, further research is needed to define BMI categories that may affect the risk of adverse maternal and neonatal outcomes. Ideally, representation from Africa and South Asia would strengthen the translation of this work. This review complements existing individual patient data evidence by including a broad range of studies and outcomes, identifying key gaps to guide future individual patient data priorities.

Policy implications

Our findings inform and support the pressing need for optimised, evidence based WHO international GWG reference standards based on individual patient data, with applicability across the full BMI range in diverse global populations. Such standards are essential to underpin policy, system, and individual level interventions to improve maternal and neonatal outcomes worldwide.

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Contributors: RFG developed the search strategy and wrote the first draft of the manuscript with HT and AM. RFG, MBK, CTT, LM, CLH, AR, SL, BB, MCFU, CMM, MAS, EB, and AM did screening, data extraction, and risk of bias appraisal. PS and SR did the statistical analyses and produced the forest plots. JL did cross checking, additional data extraction, and data cleaning and formulated tables. HT and AM had equal contribution as shared senior authors. During the preparation of this work, the authors used ChatGPT to assist with language editing. All authors reviewed and edited the manuscript and provided significant intellectual input in line with ICMJE criteria for authorship. All authors approved the manuscript for publication. The corresponding author attests that all listed authors meet authorship criteria and that no others meeting the criteria have been omitted. RFG, HT, and AM are the guarantors.

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GWG Steering Committee at the time of the study; this role was independent of the present research; no other relationships or activities that could appear to have influenced the submitted work.

Ethical approval: This study used published data and ethics approval was not required.

Data sharing: The original individual study data used is available for data sharing on reasonable request. The Github database was used to store the code used to analyse data (supplementary file 9): https://github.com/Parneet-Sethi/BMJ_Meta-Analysis.git.

Transparency: The lead authors (the manuscript's guarantors) affirm that the manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as originally planned (and, if relevant, registered) have been explained.

Dissemination to participants and related patient and public communities: The findings of this systematic review and meta-analysis will be disseminated through conference presentations, education sessions for healthcare professionals, social media, newsletters, and direct outreach to government and stakeholders such as patient organisations and commonly used public sources of patient information.

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Web appendix: Supplementary materials

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