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Assessment and interpretation of micronutrient status during pregnancy

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Accurate assessment of maternal micronutrient status is critical to the prevention of suboptimal micronutrient status and anaemia during pregnancy. Measurement of Fe, folate and vitamin B_{12} status is complicated by adaptive changes to maternal and placental physiology that markedly affect concentrations of circulating micronutrients and their functional biomarkers. Validation of new assessment methods by comparison with gold standards is often prevented by ethical considerations. Antenatal screening in the UK is predominantly concerned with the detection of anaemia, although estimation of maternal Fe stores by serum ferritin at the start of antenatal care may be a more effective preventive strategy. Functional assessment of maternal anaemia is highly problematic, so instead reference data are used for its definition. The effect of mild-to-moderate anaemia on pregnancy outcome is unclear because of the crude nature of its assessment and the influence of confounding factors. Fe-deficient erythropoiesis may be detected by assessment of erythrocyte Zn protoporphyrin and reticulocyte Hb, although such measures may be unavailable in many clinical laboratories. Serum soluble transferrin receptor is highly responsive to tissue Fe deficiency and is less affected by inflammation than most other indicators. Direct inter-assay comparison of serum and erythrocyte folate values is inadvisable since recovery rates differ greatly between methods. Serum total homocysteine is a useful functional biomarker of both folate and vitamin B_{12} status but during pregnancy is influenced by other factors that reduce its sensitivity. Isotope-dilution liquid chromatography–tandem MS and serum holo-transcobalamin provide new opportunities to gain detailed data of folate species and vitamin B_{12} fractions in large samples.

Micronutrient status: Pregnancy: Assessment methods: Maternal anaemia

Adequate micronutrient nutrition is essential during pregnancy to ensure optimal fetal growth[1]. Whilst a wide range of micronutrient deficiencies is commonly found in developing countries[2], concern in countries such as the UK is focused on a few micronutrients such as folate, vitamin B_{12}, Fe and vitamin D[3–6].

Pregnancy is a time of huge changes in maternal physiology, several of which may influence micronutrient concentrations and biomarkers to an extent not seen in non-pregnant non-lactating (NPNL) women[7,8]. Ethical constraints often prevent indicators of micronutrient status from being rigorously assessed in pregnant women because of the invasive nature of most gold standard methods. In the absence of specific validation studies there remains a danger that normal assessment methods and reference ranges will be assumed to be valid and that interpretation will not account for the adaptive maternal, placental and fetal responses to increased micronutrient demands during pregnancy. The present review discusses the assessment of Fe, folate, and vitamin B_{12} status in pregnant women and describes the methods used to screen routinely for maternal anaemia caused by prolonged deficiency of any of these micronutrients.

Abbreviations: CHr, reticulocyte Hb content; IDA, Fe-deficiency anaemia; IDE, Fe-deficient erythropoiesis; MCV, mean corpuscular volume; NPNL, non-pregnant non-lactating; RCF, erythrocyte folate; sTfR, soluble transferrin receptor, TC, transcobalamin; tHcy, total homocysteine; ZnPP, zinc protoporphyrin.

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Routine antenatal screening for anaemia caused by micronutrient deficiency

Anaemia can be defined as an insufficient erythrocyte mass to deliver adequate amounts of O_2 to peripheral tissues[9]. Maintenance of the erythrocyte mass is limited by the ability of maturing erythroblasts to acquire sufficient amounts of Fe, folate and vitamin B_{12} for the synthesis of DNA and haem[10]. These micronutrients can be mobilised from body stores, absorbed from the diet or recycled from senescent erythrocytes[10,11]. During pregnancy the demand for micronutrients, especially Fe and folate, is greatly increased and maternal body stores and dietary intake may be insufficient to meet demand. Inadequate supply of these micronutrients to the bone marrow results in dysfunctional erythropoiesis and ultimately anaemia.

In many industrialised countries routine antenatal care involves screening for anaemia at the initial booking appointment, normally between 10 weeks and 20 weeks of gestation, and at 28 weeks of gestation[12]. In the UK screening relies heavily on the full blood count, an array of haematological indices that provides information on the number, size and Hb content of the erythrocyte population. An abnormal result or suspicion of increased risk justifies the use of more precise methods to identify underlying problems. Most patients, however, are assessed using only full blood count data.

Mean corpuscular volume: the multi-purpose screening tool

The mean corpuscular volume (MCV) is used to screen for folate, vitamin B_{12} and Fe deficiency and is measured as part of the full blood count. Poor folate or vitamin B_{12} status increases MCV by impairing DNA synthesis and cell division, whereas Fe deficiency decreases MCV as a result of impaired Hb production[9]. The normal range in NPNL adult women is 80–100 fl, although during pregnancy this level is elevated slightly because of the physiological increase in the proportion of younger larger erythrocytes[8,13]. When screening for Fe-deficiency anaemia (IDA), MCV is considered alongside Hb and packed cell volume.

The detection of anaemia by MCV tends to occur only after functional deficiency lasting several weeks or more, since it takes time to repopulate the erythrocyte mass with enough cells of abnormal size to affect the mean markedly. Sensitivity is further reduced during pregnancy since the physiological increase in MCV can potentially mask the early stages of microcytosis[8]. It is therefore most useful at the initial booking appointment since it can identify pre-existing micronutrient deficiency that can be treated in time to prevent further deterioration[14–16]. During late pregnancy, however, it may fail to detect individuals with recently-developed deficiency brought about by the high demand for micronutrients[17,18].

Hb: the maternal oxygen-carrying capacity

The conceptus is totally dependent on the maternal supply of O_2 for its own respiration and this supply is delivered to the placenta, bound to Hb, at a rate governed by several factors including cardiac output, ventilation rate, uterine blood flow, smoking, altitude and packed cell volume[19]. Insufficient supply of Hb to the placenta caused by maternal anaemia can potentially result in fetal hypoxia with serious adverse consequences for fetal development[20].

Impaired Hb production during pregnancy is most often caused by poor Fe status, and therefore measurement of Hb serves as a useful screening method for the detection of IDA. Assessment is complicated by the physiological expansion of the plasma volume during early pregnancy and the subsequent increase in erythrocyte mass[21,22]. The net result of these haematological changes is a 5–15 % dilution of the maternal blood supply, which reduces blood viscosity and improves substrate delivery to the placenta[23,24]. This process is called the 'physiological anaemia of pregnancy' and does not reflect any deterioration in maternal Fe status or O_2-carrying capacity.

There is considerable debate as to what constitutes the optimal Hb range during pregnancy. The US Centre for Disease Control has classified maternal anaemia based on data from healthy Fe-supplemented mostly-Scandinavian pregnant women[25–28]. Using the 5th percentiles from these groups to define the limit of the normal range, the Centre for Disease Control has defined anaemia as Hb <110 g/l during the 1st and 3rd trimesters and <105 g/l during the 2nd trimester. Similarly-derived cut-off points have also been established for packed cell volumes. A more recent dataset of several hundred healthy pregnant Danish women has found similar results. Normal ranges (g/l), defined as means $\pm 1{\cdot}96$ SD, were: 118 (105–132) at 18 weeks of gestation, 118 (103–134) at 32 weeks of gestation, and 124 (108–140) at 39 weeks of gestation[8]. These values are assumed to represent a healthy range of values within these populations, since no clinically-significant adverse pregnancy outcomes were recorded. Hb concentrations below these lower cut-off points are considered likely to reflect maternal IDA to some extent.

The effects of uncomplicated IDA in human pregnancy are difficult to ascertain since ethical considerations often prevent controlled studies from being carried out. One alternative is to observe the relationships between IDA and pregnancy outcomes in free-living populations. Unfortunately, such studies are confounded by factors such as inadequate haemodilution[29,30], smoking[31], chronic inflammation[32], infection[33,34] and low BMI[34], all of which have strong independent effects on pregnancy outcome. Most studies have reported the optimal Hb range in mid-to-late pregnancy to include mild anaemia as defined by Centre for Disease Control values (Hb 95–110 g/l)[35–38] and a few have even questioned the risks associated with moderate or severe IDA (Hb <95 g/l and <80 g/l respectively), since the numerous observational studies that have examined this issue are highly inconsistent[23].

An alternative method is to examine the effects of maternal anaemia in highly-controlled animal models. Most of these studies have used ovine models, although in studies that have been carried out in human subjects using non-invasive techniques the results have generally been in agreement[20,39,40]. These results show adaptive responses by both mother and fetus to acute falls in maternal packed

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cell volume that help to prevent maternal and fetal hypoxia. The affinity of Hb for O_2 is reduced by increasing erythrocyte concentrations of 2,3-diphosphoglycerate, which allows more efficient uptake of O_2 by maternal and fetal tissue[39,41]. Increased maternal cardiac output and utero–placental blood flow maintains the rate of O_2 delivery[20,40] and increased fetal heart rate and blood pressure maintains the distribution of O_2 to fetal tissue[42]. In addition, both mother and fetus may reduce their rates of physical activity to levels that require less O_2. Only when O_2 delivery falls to below 50% of normal levels, or when conditions persist for several days, does the rate of fetal O_2 consumption fall as a linear function of O_2 delivery[43,44]. Under such conditions the fetus adapts to the lower supply of O_2 by up regulating erythropoiesis and down regulating fetal growth, both of which help to prevent the onset of hypoxia or acidosis in all but the most extreme conditions.

Whilst the effects of mild maternal anaemia remain highly controversial, moderate-to-severe anaemia in both animal models and human observational studies has been consistently associated with fetal growth restriction, probably mediated by chronically-impaired maternal O_2-carrying capacity[20,41,45,46]. However, it remains unclear whether there is any discernable benefit of Fe therapy in terms of pregnancy outcomes, other than restoration of maternal Fe status[15]. The continuing practice of prophylactic Fe supplementation is based on the general consensus that Fe deficiency is by definition undesirable and that its prevention is more likely to be beneficial than harmful[47]. Maternal supplementation during pregnancy is also likely to improve neonatal Fe status and thus protect the infant from IDA, especially if born preterm[47–49].

Assessment of maternal body iron stores

Body Fe stores are located mostly in the reticuloendothelial cells of the bone marrow, liver and spleen, as well as in hepatocytes[50]. The largest pool of Fe is contained in the maternal erythrocyte mass, which is constantly turned over and recycled. The most precise methods for the assessment of body Fe stores are quantitative phlebotomy[51], liver biopsy[52], MRI[53] and bone marrow staining[54]. However, the routine use of such techniques during pregnancy would be both unethical and expensive.

Fortunately, body Fe stores can be measured quite accurately using serum ferritin. Ferritin serves as the body's main intracellular Fe storage protein. Trace amounts of mostly Fe-free ferritin are secreted into the plasma from reticuloendothelial or parenchymal cells in concentrations that linearly reflect total body Fe stores[55]. In NPNL women a serum ferritin concentration of 1 μg/l is equivalent to approximately 7–8 mg mobilisable Fe[56]. Thus, a serum ferritin concentration of 50 μg/l indicates adequate Fe stores (350–400 mg) for the day-to-day needs of most NPNL women. However, as >500 mg Fe stores is required to prevent depletion of Fe stores during the average pregnancy[57], only serum ferritin concentrations of >70–80 μg/l in early pregnancy are likely to reflect sufficient Fe stores able to prevent depletion without the need for supplementation[58,59].

The interpretation of serum ferritin is based not on reference data from healthy individuals, as with the detection of IDA, but rather on the concentrations at which depleted body Fe stores can be predicted with great confidence. In NPNL individuals a serum ferritin of <15–16 μg/l identifies the absence of stainable bone marrow with 75% sensitivity and 98% specificity[60,61]. Only one study has carried out similar assessments of pregnant women[62]. In this study the most accurate cut-off point in late pregnancy was determined to be 30 μg/l, which is markedly higher than that found in NPNL women. Sensitivity and specificity at this level are 90·0% and 85·1% respectively, compared with 37·5% and 93·7% for 12 μg/l; data for the commonly-used cut-off at 15 μg/l were not presented.

The higher cut-off point found in this study may have been a result of the high levels of inflammation in the sample. Pregnancy is associated with a physiological increase in inflammatory biomarkers, especially during the 1st and 3rd trimesters[63,64]. Serum ferritin becomes elevated during inflammation because of its role as an acute-phase reactant, and therefore may overestimate body Fe stores[65]. High serum ferritin can also result from damage to ferritin-rich tissues that releases it into the maternal circulation, such as can occur in cases of pre-eclampsia[66]. Inflammation and infection tend to affect the entire serum ferritin distribution, not just those individuals with high concentrations[67] and therefore, whenever possible, serum ferritin should be measured alongside inflammatory markers such as C-reactive protein, α1-antichymotrypsin, α1-acid glycoprotein or erythrocyte sedimentation rate[68,69].

The relationship between serum ferritin and pregnancy outcome is confounded by several of the same factors that complicate the assessment of anaemia. Maternal infection, inflammation and hypertensive disorders are all associated with a higher incidence of preterm delivery and fetal growth restriction[70–73]. Thus, whilst it appears from observational studies that serum ferritin concentrations <30 μg/l during the second half of pregnancy are protective[62], this is most probably because the risks associated with these confounders are much greater than those associated with depletion of maternal Fe stores. It is unlikely that there are any beneficial effects of maternal Fe stores depletion *per se*, since healthy women supplemented with Fe from early pregnancy experience no increase in adverse pregnancy outcomes and are less likely to become Fe deficient[74].

Assessment of iron-deficient erythropoiesis

Fe-deficient erythropoiesis (IDE) is the synthesis of erythrocytes deficient in Hb as a result of a lack of available Fe. The main difference between IDE and IDA is that IDE reflects current erythrocyte production whereas IDA reflects the state of the erythrocyte population as a whole. As only 1–2% of the erythrocyte mass is replaced each day, it can take several weeks of IDE before its effects become clinically apparent in the form of anaemia.

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Conversely, once effective Fe therapy begins IDE will cease yet IDA can persist for several weeks until a substantial proportion of the erythrocyte population is replaced by normochromic normocytic cells[75].

Although the reduced O_2-carrying capacity caused by IDE may be compensated by an array of adaptive responses, depletion of tissue Fe has widespread, if not clinically-apparent, effects on the maternal metabolism. Reductions in cellular Fe concentrations may adversely affect the function of a wide range of Fe-dependent tissue enzymes such as catalases, peroxidises and cytochromes[76,77]. The early detection and treatment of IDE is therefore important not only to prevent the onset of IDA, but also to ensure optimal Fe-dependent metabolism throughout pregnancy.

Erythrocyte zinc protoporphyrin

The most established biomarker of IDE is zinc protoporphyrin (ZnPP), which measures the extent to which Zn, rather than Fe, has been chelated with protoporphyrin. Increasing amounts of ZnPP are produced in maturing erythroblasts as Fe availability becomes suboptimal in the bone marrow. This process may function as a homeostatic mechanism by inhibiting the excretion of Fe following haemolysis by macrophages[78]. Thus, it is a highly-sensitive functional indicator of IDE, especially when presented as ZnPP:haem, as this variable controls for haemodilution during pregnancy[79]. ZnPP remains constant throughout pregnancy in Fe-replete women, whereas in unsupplemented women it tends to rise markedly in the last trimester[80,81].

Although ZnPP measures IDE with reasonable accuracy, it cannot distinguish between true and functional Fe deficiency. The latter occurs when body Fe stores are adequate yet Fe is not available to the bone marrow, such as can happen during infection and inflammation. The underlying cause of IDE may be identified by concurrent assessment of serum ferritin. For instance, if both measures are high then IDE caused by chronic inflammation is more likely, whereas if ZnPP is high ($\geq 60\,\mu$mol/mol haem) and serum ferritin is low ($<15\,\mu$g/l) then true IDE caused by depleted Fe stores is more likely. This combined use of ZnPP and ferritin values has been recommended by several authors as a reliable method for the determination of IDE[82,83]. However, it should be noted that functional and true IDE are not mutually exclusive processes and may co-exist, especially during late pregnancy when low-level inflammation with depleted Fe stores is a common occurrence. In such circumstances the relative contributions of the underlying causes of IDE may be difficult to quantify.

The main advantages of ZnPP are its cost efficiency and its ability to be used in the field by unspecialised personnel using a portable haematofluorometer. However, its use is limited by its high sensitivity to environmental Pb pollution[84], which inhibits the binding of Fe to protoporphyrin, and its poor sensitivity in identifying improvements once Fe therapy has begun. This limitation might be resolved if the assay could be refined to measure only reticulocyte ZnPP, as has been suggested by some authors, and initial crude efforts to this effect have shown considerable promise[85]. Despite its advantages, however, the lack of an automated method for assessment of ZnPP has severely constrained its use in most clinical laboratories.

Reticulocyte indices

Reticulocytes are immature erythrocyte cells that under normal conditions comprise about 1% of the erythrocyte population. They mature in the bone marrow for 1–3 d and are then released in the maternal circulation for 1–2 d before they lose their RNA and become fully mature. Reticulocyte counts have been available in most clinical laboratories for many years as a measure of the rate of erythropoiesis. However, a few modern haematological analysers now have the ability to measure the Hb content of reticulocytes, which effectively measures the extent of IDE over the previous 3–4 d[86].

Reticulocyte Hb content (CHr) is similar in some aspects to ZnPP. It is a cellular measure of IDE that on its own does not distinguish between true and functional Fe deficiency. However, unlike ZnPP, analysis is restricted to reticulocytes, so its sensitivity to short-term changes in Hb production is much greater[87]. Values <26–28 pg identify IDE in NPNL adults[88].

CHr works by assessment of the reticulocyte cell volume and Hb content; hence conditions that change MCV independently of Fe deficiency will lower the precision of Chr[89]. Such conditions include microcytosis caused by thalassaemia and macrocytosis caused by folate or vitamin B_{12} deficiency[90]. Unfortunately, concurrent Fe and folate deficiency is relatively common during late pregnancy[91]. Whilst initial validation studies seem to suggest that CHr is an accurate method of assessing IDE in pregnancy, the effects of suboptimal folate or vitamin B_{12} status may be important sources of error during pregnancy that require further study.

CHr is essentially a short-term indicator, but it can now be measured alongside the percentage of hypochromic erythrocytes, which until recently had only been available by manual blood film[86]. Together CHr and the percentage of hypochromic erythrocytes appear to offer the most accurate assessment of past and present IDE and IDA during pregnancy[92]. However, determination of the underlying cause of IDE may require additional assessment of tissue Fe levels.

Assessment of maternal tissue iron depletion

The maintenance of serum Fe concentrations is dependent on the export of Fe from storage cells such as the duodenal mucosa, macrophages and hepatocytes[93]. As these stores become depleted, the proportion of serum transferrin saturated with Fe (transferrin saturation) decreases. In response, the serum concentration of transferrin (the total Fe-binding capacity) is increased to promote uptake and delivery of Fe to dependent tissues such as the bone marrow or placenta. The classical signs of tissue Fe deficiency are therefore low serum Fe ($<400\,\mu$g/l), high serum total Fe-binding capacity ($<2160\,\mu$g/l), and low transferrin saturation ($<16\%$)[47,94].

By mid–late pregnancy tissue Fe deficiency is common as a result of sustained demand for Fe during the expansion

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Table 1. Laboratory measures of maternal iron status

Body Fe storage	Tissue Fe depletion	Fe-deficient erythropoiesis	Total body Fe
'Adequacy' should be based on current Fe stores as measured by serum ferritin, relative to future needs during pregnancy 1st Trimester >75 μg/l 3rd Trimester >30 μg/l Markers of inflammatory status useful to establish reliability of values; bias likely during late pregnancy	↑sTfR >8·5 mg/l ↓Total body Fe <0 mg/kg ↓Serum Fe <400 μg/l ↓Serum ferritin <12 μg/l, no longer linear but still associated with tissue deficiency sTfR not significantly affected by inflammation, unlike other indicators. However, sTfR:ferritin will incorporate acute phase reactivity of ferritin	Short-term indicators used for assessment of impaired Hb synthesis: ↑ZnPP ≥ 60 μmol/mol haem ↓CHr ≤ 28·8 pg Long-term indicators used for assessment of anaemia: ↓MCV <80 fl ↓Hb <110 g/l; <105 g/l (2nd trimester) ↓Hct <33·0%; <32·0% (2nd trimester) ↓HYPO% >3·4%	Calculated according to Skikne *et al.*[108]: body Fe (mg/kg) = −(log(sTfR:ferritin) − 2·8229)/0·1207 Possible error during pregnancy as a result of erythropoiesis and inflammation Useful indicator for intervention studies to improve maternal Fe status

sTfR, soluble transferritin receptor; ZnPP zinc protoporphyrin; CHr, reticulocyte Hb content; MCV, mean corpuscular volume; Hct, packed cell volume; percentage of hypochromic erythrocytes; ↑, increased; ↓, reduced.

of the erythrocyte mass and development of the conceptus. However, during the last trimester (27–40 weeks) the fetus starts to grows at its maximal rate and accumulates Fe stores in preparation for infancy[49,57]. If during this period maternal serum Fe concentrations are suboptimal, placental Fe uptake may be maintained by up-regulation of placental transferrin receptors[95,96] and modulation of Fe regulation in the maternal gut[97]. However, such mechanisms are not always able to compensate sufficiently to prevent reduced rates of fetal Fe accretion[49,98]. Accurate identification of maternal tissue Fe deficiency during pregnancy is therefore essential to prevent suboptimal Fe status in the infant.

Serum total Fe-binding capacity is increased by steroid hormones such as oestrogens[99], which during pregnancy are found in high concentrations in maternal plasma. Even Fe-replete women with constant serum Fe tend to show increasing total Fe-binding capacity and falling transferrin saturation with advancing gestation[80,100–102]. As a result it may be preferable during pregnancy to concentrate entirely on the direct measurement of serum Fe[49,103].

Serum Fe measures the transferrin-bound Fe available for maternal and placental uptake. It has a high level of intra-individual and diurnal variability, and may reflect recent dietary intake, especially following use of supplemental Fe[104,105]. It is highly reactive to infection and inflammation since both Fe uptake from the gut and Fe release from macrophages are down-regulated by the action of hepcidin, a regulator of Fe homeostasis[106]. These limitations may be overcome to some extent by sufficient sample size, careful study design and repeated measurements. However, its susceptibility to such large day-to-day fluctuations makes it a crude indicator of maternal tissue Fe status and of little diagnostic utility in the individual.

A general summary of Fe biomarkers during pregnancy is shown in Table 1.

Serum soluble transferrin receptor

Soluble transferrin receptors (sTfR) are truncated versions of the transferrin receptors that facilitate cellular uptake of Fe-rich plasma transferrin. Expression of transferrin receptors is inversely related to that of intracellular ferritin, since both are mediated by Fe-responsive elements whose main purpose is to maintain intracellular Fe concentrations[107]. Expression of transferrin receptors therefore increases as tissue Fe levels fall, resulting in higher concentrations of sTfR in the serum[108]. The density of transferrin receptors is highest in cells with the greatest demand for Fe, such as immature erythroid cells, hepatocytes and the placenta[109].

Serum sTfR has a high specificity to tissue Fe deficiency and a low sensitivity to acute or chronic inflammation, unlike most other indicators of Fe status[110,111]. When combined with measurement of serum ferritin, the sTfR:ferritin can be used to estimate total body Fe (mg/kg) with high precision[112].

However, the accuracy of sTfR and sTfR:ferritin during pregnancy has not yet been firmly established. As a large proportion of sTfR is derived from eythroid precursors in the bone marrow, changes in the rate of erythropoiesis also affect sTfR concentrations. In Fe-replete individuals sTfR is an accurate indicator of erythropoiesis[113], whereas in those individuals with a steady rate of erythropoiesis sTfR is an accurate indicator of tissue Fe depletion[114].

Unfortunately, pregnancy is associated with marked changes in both erythropoiesis and body Fe stores that introduce considerable uncertainty as to the primary cause of changes in sTfR concentrations. There are few data on the normal patterns of erythropoiesis during pregnancy, mainly because of the prohibitive nature of radio Fe studies, and therefore it is not possible to adjust for the influence of erythropoiesis at each stage. During pregnancy raised sTfR may in fact be more strongly predicted by the rate of erythropoiesis than by Fe status[115].

Some studies have reported sTfR to be a sensitive and specific measure of tissue Fe deficiency in pregnancy[116,117], but these have not had the benefit of comparison with gold standard methods, as has been the case for NPNL subjects. sTfR and the sTfR:ferritin appear to have great potential as indicators of tissue Fe depletion, but their validity during pregnancy remains uncertain until the effects of erythropoiesis can be ascertained. In the meantime, sTfR:ferritin is probably of most use as a method of

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evaluating the effectiveness of interventions to improve Fe status during pregnancy, since the error as a result of erythropoiesis and inflammation ought to be similar in both control and intervention groups[112].

Direct assessment of folate status

Most pregnant women in the UK will only be screened for folate deficiency by assessment of MCV. However, such assessment is highly insensitive, especially in the presence of concurrent Fe deficiency, and is unable to specify the underlying cause. The most common method of directly assessing folate status is serum or plasma folate. This short-term indicator is highly sensitive to recent folate intake and indicates the amount of folate being taken up by tissues, catabolised and excreted at the point in time when the serum sample was drawn[118]. It is markedly and quickly decreased during negative folate balance, when tissue demands exceed that provided by dietary supply[119].

The advantage of serum folate in studies of pregnant women is that it represents the concentration available for placental uptake at the time of blood sampling, whereas erythrocyte folate (RCF) represents average availability over several months. As folate demands change several fold between trimesters, analysis of serum folate allows time-specific determination of folate availability. In NPNL individuals serum folate and dietary folate intake are generally well correlated. However, during pregnancy this correlation may be weakened[120].

RCF concentrations indicate the availability of folate at the time when the cell was forming in the bone marrow[121]. Once DNA synthesis ceases in maturing erythrocytes, the remaining folate concentrations are relatively static until erythrophagocytosis, when the folate is recycled. The mean RCF concentration therefore reflects a moving average of serum folate status over the 120 d lifespan of the erythrocyte population. As this period also approximately corresponds to the time in which hepatic folate stores become depleted on a folate-free diet[122], RCF concentrations are assumed to correlate with those in tissue[123]; this correlation has been confirmed by examination of liver and RCF concentrations in subjects with chronic alcoholism[124]. However, the validity of this assumption during late pregnancy, when both folate and erythrocyte turnover are markedly different from that during the NPNL state[125], remains untested.

RCF is standardised by packed cell volume and is therefore not confounded by variation in plasma volume expansion. Values <140–150 μg/l for RCF or <3 μg/l for serum folate are generally considered to be indicative of folate deficiency in the NPNL state[126].

Both serum folate and RCF are most often measured by methods that use high-affinity folate-binding proteins such as RIA, ion-capture assays and chemiluminescence. Microbiological assays using various strains of *Lactobacillus casei* have traditionally been used as the reference standard and some are now fully automated and cost efficient[127]. However, they can sometimes be confounded by antibiotics, the use of which may be relatively common during pregnancy, and are therefore not often used in clinical contexts.

Although folate-binding protein assays have been widely used, persistent doubts have been raised about their reliability[128–130]. A round-robin international survey of reputable laboratories found inter-assay CV of 32–41% with RCF and 17–48% with serum folate[131]. The variability of high or low values was found to be much greater than that for mid-range concentrations. Much of the difference been attributed to the types of reference standards in commercial assays, which were found to vary considerably by manufacturer. Recent efforts to standardise these reference materials in whole blood[132] and serum[133] may substantially reduce inter-assay variability in the future, thus making comparison of absolute values between studies more reliable.

Although generally folate-binding-protein assays tend to underestimate folate status as a result of incomplete recovery of 5-methyltetrahydrofolate[134], they may actually overestimate folate status during pregnancy. A comparison of four different methods for assessing RCF in pregnant and non-pregnant women[135] has reported major inter-assay differences, with RIA giving approximately 40% greater values than *L. casei*[135]. Whilst the folate status of pregnant and non-pregnant women were not found to be significantly different when measured using *L. casei* and GC–MS, the values for pregnant women according to the folate-binding-protein assays were found to be higher than those of the non-pregnant women.

A recently-developed method using isotope-dilution liquid chromatography–tandem MS now enables high-throughput analysis of folate status with high precision and the ability to differentiate between folate species[136]. This method represents a considerable advance in the ability to examine the complex inter-relationships between folate species and may help to resolve the emerging debate about the risks associated with unmetabolised folic acid in plasma[137,138]. Recent comparative studies have shown excellent agreement between liquid chromatography–MS–MS and *L. casei*[134].

The lack of comparability between laboratories has led to the classification of inadequate folate status being generally based on comparison with reference data from local populations and not on symptoms of functional folate deficiency such as neutrophil hypersegmentation or macrocytosis. Such an approach may be preferable since during pregnancy these functional indices are less reliable than during the NPNL state. Neutrophils tend to hyposegment with advancing gestation, which can mask folate deficiency[139], and MCV may sometimes be more influenced by the microcytic effects of poor maternal Fe status during late pregnancy, as seen in pregnant adolescents from the About Teenage Eating Study (Fig. 1). However, the use of reference population data to determine folate status is complicated by the increasing amount of food now fortified with folic acid in modern diets, especially fortified flour, since normal ranges in some populations are now higher than those of previous generations[140]. As a result, the use of normality-based approaches is not only incompatible between countries with different fortification strategies, but is unlikely to be a sensitive method of detecting functional folate deficiency in pregnancy.

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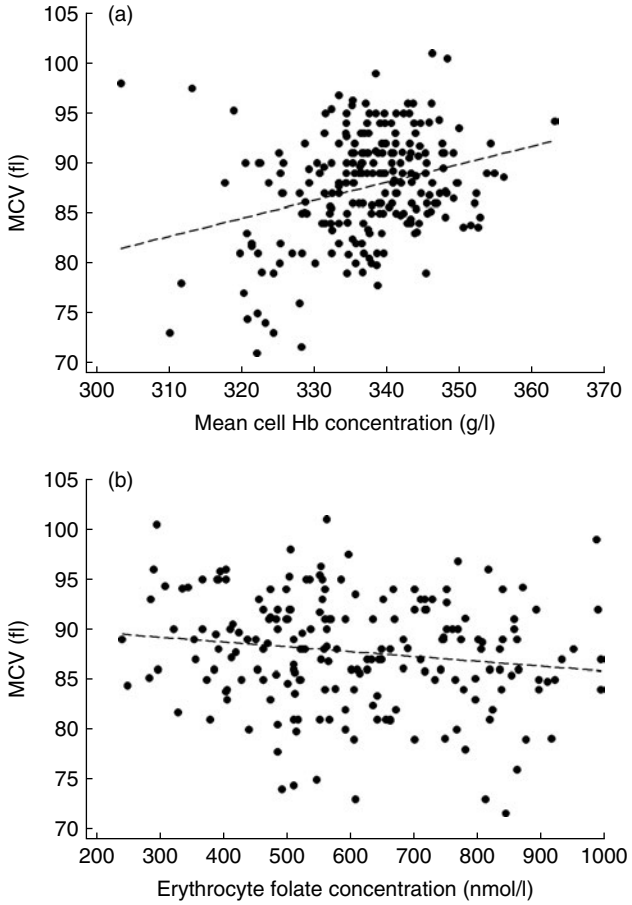

Fig. 1. Conflicting influences on mean corpuscular volume (MCV) in 239 pregnant adolescents from the About Teenage Eating Study measured during the third trimester of pregnancy. Mean cell Hb concentration was calculated as the Hb concentration divided by the packed cell volume; erythrocyte folate concentrations were similarly standardised. (a) r_p 0·30, $P<0·001$; (b) r_p −0·13, $P=0·04$. (Data from S. Wheeler, unpublished results.)

Functional biomarkers of folate status

Serum total homocysteine

Functional indicators can provide useful information that direct measurement of vitamin concentrations cannot, and are often more sensitive. A widely-used functional biomarker of mild or occult folate depletion is serum total homocysteine (tHcy). tHcy is primarily a functional marker of folate status in Western populations, but is also affected by the status of other nutrients such as vitamin B_{12}, vitamin B_6, methionine, betaine, choline and riboflavin, all of which are involved in homocysteine production or excretion[141–143].

A major advantage of tHcy over serum folate is that it does not require fasting blood samples, the collection of which may be ethically prohibited in studies of pregnant women. Postprandial serum tHcy concentrations are generally slightly lower than fasted values but these differences are small compared with the total amount of day-to-day variation[144,145]. Serum folate, on the other hand, can reflect recent intake, especially when consumed in relatively high doses such as those found in antenatal folic acid supplements[146].

During pregnancy the correlation between folate status and tHcy becomes weaker with advancing gestation. Serum tHcy falls markedly during the first 20 weeks of gestation to approximately half that of NPNL levels and then increases slowly back to pre-conceptual levels by parturition[147]. This uncoupling with folate concentrations, which in unsupplemented subjects continue to fall throughout pregnancy, remains poorly understood. The decline in serum tHcy in the first half of pregnancy has been suggested to be the result of plasma volume expansion, increased renal clearance, decreased serum albumin and higher concentrations of oestrogens, most of which have been eliminated as causal factors[73]. Oestrogens have been suggested as the most probable mediators, but their homocysteine-lowering effects have recently been questioned[148,149].

Despite its idiosyncratic behaviour during pregnancy, serum tHcy remains a sensitive functional biomarker of folate status in pregnant women. Precision may be further increased by adjustment for confounding factors such as renal function, smoking, vitamin B_{12} status and coffee intake[150,151]. A plasma tHcy concentration >15 μmol/l is generally used to define mild hyperhomocysteinaemia in NPNL women, but because of the physiological decrease in plasma tHcy concentrations during pregnancy, an upper reference limit of 10 μmol/l has been recommended by an expert panel[150]. Whilst there have been problems with tHcy assessment in the past, most modern assays now have good levels of precision and comparability[150].

p-Amino- and acetamido-benzoylglutamate

The rate of folate turnover can be quantified by measurement of the folate catabolites p-amino-benzoylglutamate and acetamido-benzoylglutamate present in serum or urine[152]. Until recently, the analysis procedure has required extensive sample preparation and clean up[153], making it unsuitable for clinical or epidemiological use. However, recent innovations using liquid chromatography–MS–MS have simplified this process greatly, such that high-volume analysis of urinary and serum p-amino-benzoylglutamate and acetamido-benzoylglutamate may be both possible and cost effective in the future[154,155]. Analysis of p-amino-benzoylglutamate may also have potential as a biomarker of folate status in degraded blood samples[155].

Measurement of folate turnover is not a measurement of folate status *per se*. It does, however, provide detailed information on an individual's folate requirement, since the amount excreted can be assumed to be the amount required to replace it in order to prevent depletion. The analysis of p-amino-benzoylglutamate and acetamido-benzoylglutamate, together with conventional assessment of folate status, may enable more detailed examination of the relationships between folate demands over the course of pregnancy and maternal folate status, which hitherto has been restricted to samples of less than ten individuals[152,156].

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Poor folate status and pregnancy outcomes

The placenta is rich in high-affinity folate receptors that are able to maintain folate delivery to the fetus even at relatively low maternal plasma concentrations[142]. However, cord and placental folate concentrations are still dependent on those in maternal plasma[157]. Poor folate status has been strongly, if somewhat inconsistently, associated with several adverse pregnancy outcomes, such as preterm delivery, pre-eclampsia, stillbirth, spontaneous abortions, placental abruption, fetal growth restriction and congenital birth defects[158–162]. Raised tHcy is also associated with these risks, although it is not yet clear what proportions are the result of poor folate status *per se* or to the folate-independent actions of homocysteine[156,157]. The preventive effect of folic acid supplementation in substantially reducing the risk of neural-tube defects has been proven in several randomised controlled trials[163,164]. However, whilst the reduction in the incidence of neural-tube defects has been a tremendous accomplishment of nutrition research, it has also resulted in the situation in which it is now unethical to conduct placebo-controlled intervention trials to determine the effects of folic acid supplementation during pregnancy, since the periconceptual use of 400 µg folic acid is now part of routine antenatal care. Hence, the ability to test the associations between poor folate status and other pregnancy outcomes under controlled conditions is severely limited.

Assessment of vitamin B_{12} status

Serum cobalamin

The accurate detection of vitamin B_{12} deficiency during pregnancy is extremely difficult. In normal NPNL subjects and in patients with pernicious anaemia serum cobalamin generally correlates well with tissue concentrations, although kinetic studies have shown that concentrations in serum tend to be preserved at the expense of those in tissue[165,166]. As a result, low serum cobalamin is only likely to become apparent with moderate or severe tissue deficiency. Serum cobalamin of <150 ng/l is generally associated with clinically-apparent deficiency in the NPNL state, yet the usefulness of this, or indeed any, cut-off during pregnancy is questionable[167]. Concentrations below this level have been found in pregnant women with dietary intakes well in excess of the US RDA of 2·6 µg/d and no corroborative clinical or biochemical evidence of deficiency[168,169].

Functional biomarkers: serum total homocysteine and serum methylmalonic acid

As serum cobalamin is less sensitive during pregnancy, mild or occult vitamin B_{12} deficiency may be more easily detected with functional biomarkers such as serum methylmalonic acid and serum tHcy. Vitamin B_{12} has only two functions in animal cells and impairment of either causes the accumulation of unmetabolised precursors. Methylmalonic acid becomes elevated as a result of the impairment of the cobalamin-dependent enzyme methylmalonyl-CoA mutase, which converts methylmalonyl-CoA to succinyl-CoA, an essential precursor of haem and an intermediate in the citric acid cycle. Serum tHcy accumulates as a result of the impairment of cobalamin-dependent methionine synthase[170].

Although methylmalonic acid and tHcy are more sensitive than serum total cobalamins, both have major limitations during pregnancy. Serum tHcy can be elevated by folate deficiency, which is more common than vitamin B_{12} deficiency in Western countries, and becomes uncoupled from vitamin B_{12} status with advancing gestation. Methylmalonic acid is also affected by renal clearance as well as concurrent use of antibiotics[171], and can sometimes be sporadically elevated during pregnancy for reasons as yet unknown[167,168]. Measurement of methylmalonic acid is also expensive and requires the use of techniques that may not be widely available in clinical laboratories. The use of either biomarker alone is therefore insufficient to determine vitamin B_{12} status during pregnancy, although they can provide useful supplemental data to other more direct measures.

Holo-transcobalamin

Cobalamins in human serum are transported by the two main binding proteins, haptocorrin and transcobalamin (TC). These proteins are either complexed with cobalamins (holo) or cobalamin-free (apo). Haptocorrin carries most of the cobalamins in serum, which are cleared slowly over a period of several days. However, no major function has yet been attributed to it other than the binding of metabolically-inert forms of vitamin B_{12}. TC, on the other hand, is highly active and serves as the main transporter of cobalamins from the intestine to tissues including the placenta, which is rich in TC receptors[172]. Newly-absorbed cobalamins bound to holo-TC are generally cleared from the maternal circulation within minutes, although a small amount remains in circulation.

Recent longitudinal analysis of TC and haptocorrin fractions during pregnancy has determined the reason for the decline in serum cobalamin with advancing gestation[7]. Large reductions were found in the haptocorrin fraction saturated with true cobalamins, whereas holo-TC remained stable over the whole of gestation. This finding explains why the physiological reduction in serum cobalamin during pregnancy is not associated with functional vitamin B_{12} deficiency, as haptocorrin is relatively inert.

Since TC is the main fraction available for placental uptake of vitamin B_{12}, maternal serum holo-TC concentrations are highly correlated with cord blood cobalamins and therefore reflect the maternal supply of vitamin B_{12} to the fetus[172]. Whilst the high sensitivity and specificity of maternal holo-TC makes it the most suitable biomarker for the assessment of maternal vitamin B_{12} status, the assay required for its assessment is still highly-specialised and not yet widely available. Until such time as it is suitable for high-volume low-cost throughput of samples, routine screening for maternal vitamin B_{12} deficiency will continue to be carried out using crude indicators with low sensitivity and specificity such as MCV and serum cobalamin, leaving many pregnant women at risk of subclinical vitamin B_{12} deficiency.

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Implications of poor vitamin B_{12} for fetal growth

With the notable exception of vegans, low vitamin B_{12} intakes are relatively rare in Western countries and consequently poor vitamin B_{12} status is normally a result of non-dietary factors. However, poor vitamin B_{12} status is still a major public health problem in developing countries with low consumption of animal foods, such as India and Nepal[173,174]. Studies in these countries have found similar relationships between vitamin B_{12} status and fetal growth restriction to those found with folate[175,176], although its relationships with other pregnancy outcomes remain unknown.

Summary

Interpretation of micronutrient biomarkers and indices during pregnancy is complex and should take into account the maternal, placental and fetal adaptations to pregnancy, most of which are highly variable between individuals and dependent on the gestational age at which measurement occurs. As a result of the complexity and uncertainty surrounding these factors, sensitivity and specificity of virtually all biomarkers will be reduced, especially during late pregnancy, and many of the normal ranges commonly used for NPNL individuals may be inappropriate. Current antenatal screening of micronutrient status in the UK is crude, as it is concerned primarily with the treatment rather than prevention of nutritional anaemia.

Future research should establish methods that can identify recent-onset functional deficiency without substantial bias from maternal inflammation, infection, endocrine influences, plasma volume and renal function. Several relatively new indicators of Fe status show much promise in this context, especially when used in combination. However, they require further validation in pregnant subjects. Assessment of folate status remains problematic because of issues surrounding the reliability and comparability of folate-binding-protein assays. However, new methods using liquid chromatography–MS–MS are able to measure specific folate species, including products of folate catabolism, with high precision and in large sample sizes. Similarly, measurement of serum holo-TC may provide much needed data on the relationships between vitamin B_{12} status and pregnancy outcome.

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References

1. Fall CH, Yajnik CS, Rao S, Davies AA, Brown N & Farrant HJ (2003) Micronutrients and fetal growth. *J Nutr* **133**, 1747S–1756S.
2. The Micronutrient Initiative and United Nations Children's Fund (2004) *Vitamin and Mineral Deficiency: A Global Progress Report*. Ottowa, Ont.: The Micronutrient Initiative.
3. Relton CL, Pearce MS & Parker L (2005) The influence of erythrocyte folate and serum vitamin B_{12} status on birth weight. *Br J Nutr* **93**, 593–599.
4. Rogers I & Emmett P (1998) Diet during pregnancy in a population of pregnant women in South West England. ALSPAC Study Team. Avon Longitudinal Study of Pregnancy and Childhood. *Eur J Clin Nutr* **52**, 246–250.
5. Henderson L, Irving K, Gregory J, Bates CJ, Prentice A, Perks J, Swan G & Farron M (2003) *The National Diet and Nutrition Survey: Adults Aged 19 to 64 Years*. vol. 3: *Vitamin and Mineral Intake and Urinary Analytes*. London: The Stationery Office.
6. Javaid MK, Crozier SR, Harvey NC, Gale CR, Dennison EM, Boucher BJ, Arden NK, Godfrey KM, Cooper C & Princess Anne Hospital Study Group (2006) Maternal vitamin D status during pregnancy and childhood bone mass at age 9 years: a longitudinal study. *Lancet* **367**, 36–43.
7. Morkbak AL, Hvas AM, Milman N & Nexo E (2007) Holotranscobalamin remains unchanged during pregnancy. Longitudinal changes of cobalamins and their binding proteins during pregnancy and postpartum. *Haematologica* **92**, 1711–1712.
8. Milman N, Bergholt T, Byg KE, Eriksen L & Hvas AM (2007) Reference intervals for haematological variables during normal pregnancy and postpartum in 434 healthy Danish women. *Eur J Haematol* **79**, 39–46.
9. Greer JP, Foerster J, Lukens JN, Rodgers GM, Paraskevas F & Glader B (editors) (2004) *Wintrobe's Clinical Hematology*, 11th ed. Philadelphia, PA: Lippincott Williams & Wilkins.
10. Koury MJ & Ponka P (2004) New insights into erythropoiesis: the roles of folate, vitamin B_{12}, and iron. *Annu Rev Nutr* **24**, 105–131.
11. Knutson M & Wessling-Resnick M (2003) Iron metabolism in the reticuloendothelial system. *Crit Rev Biochem Mol Biol* **38**, 61–88.
12. National Collaborating Centre for Women's and Children's Health (2008) *Antenatal Care: Routine Care for the Healthy Pregnant Woman*. 2nd ed. London: RCOG Press.
13. Lurie S (1993) Changes in age distribution of erythrocytes during pregnancy: a longitudinal study. *Gynecol Obstet Invest* **36**, 141–144.
14. United Nations Children's Fund/United Nations University/World Health Organization (2001) *Iron Deficiency Anemia: Assessment, Prevention, and Control*. Geneva: WHO.
15. Reveiz L, Gyte GM & Cuervo LG (2007) *Treatments for Iron-deficiency Anaemia in Pregnancy. Cochrane Database of Systematic Reviews 2007*, issue 1, 003094. Chichester, West Sussex: John Wiley and Sons.
16. Nybo M, Friis-Hansen L, Felding P & Milman N (2007) (Prevalence of anaemia in pregnant immigrant women compared to ethnic Danish women; article in Danish). *Ugeskr Laeger* **169**, 3586–3588.
17. Rusia U, Flowers C, Madan N, Agarwal N, Sood SK & Sikka M (1999) Serum transferrin receptors in detection of iron deficiency in pregnancy. *Ann Hematol* **78**, 358–363.
18. van den Broek NR, Letsky EA, White SA & Shenkin A (1998) Iron status in pregnant women: which measurements are valid? *Br J Haematol* **103**, 817–824.
19. Carter AM (1999) Placental oxygen transfer and the oxygen supply to the fetus. *Fetal Matern Med Rev* **11**, 151–161.
20. Mostello D, Chalk C, Khoury J, Mack CE, Siddiqi TA & Clark KE (1991) Chronic anemia in pregnant ewes: maternal and fetal effects. *Am J Physiol* **261**, R1075–R1083.

https://doi.org/10.1017/S0029665108008732 Published online by Cambridge University Press

21. Lund CJ & Donovan JC (1967) Blood volume during pregnancy. Significance of plasma and red cell volumes. *Am J Obstet Gynecol* **98**, 394–403.
22. Orsi NM & Tribe RM (2008) Cytokine networks and the regulation of uterine function in pregnancy and parturition. *J Neuroendocrinol* **20**, 462–469.
23. Rasmussen K (2001) Is there a causal relationship between iron deficiency or iron-deficiency anemia and weight at birth, length of gestation and perinatal mortality? *J Nutr* **131**, 590S–601S.
24. Chesley LC (1972) Plasma and red cell volumes during pregnancy. *Am J Obstet Gynecol* **112**, 440–450.
25. Svanberg B, Arvidsson B, Norrby A, Rybo G & Solvell L (1975) Absorption of supplemental iron during pregnancy – a longitudinal study with repeated bone-marrow studies and absorption measurements. *Acta Obstet Gynecol Scand Suppl* **48**, 87–108.
26. Puolakka J, Janne O, Pakarinen A, Jarvinen PA & Vihko R (1980) Serum ferritin as a measure of iron stores during and after normal pregnancy with and without iron supplements. *Acta Obstet Gynecol Scand Suppl* **95**, 43–51.
27. Taylor DJ, Mallen C, McDougall N & Lind T (1982) Effect of iron supplementation on serum ferritin levels during and after pregnancy. *Br J Obstet Gynaecol* **89**, 1011–1017.
28. Sjostedt JE, Manner P, Nummi S & Ekenved G (1977) Oral iron prophylaxis during pregnancy: a comparative study on different dosage regimens. *Acta Obstet Gynecol Scand Suppl* **60**, 3–9.
29. Hytten F (1985) Blood volume changes in normal pregnancy. *Clin Haematol* **14**, 601–612.
30. Salas SP, Marshall G, Gutierrez BL & Rosso P (2006) Time course of maternal plasma volume and hormonal changes in women with preeclampsia or fetal growth restriction. *Hypertension* **47**, 203–208.
31. Leifert JA (2008) Anaemia and cigarette smoking. *Int J Lab Hematol* **30**, 177–184.
32. van den Broek NR & Letsky EA (2000) Etiology of anemia in pregnancy in south Malawi. *Am J Clin Nutr* **72**, 247S–256S.
33. Muhangi L, Woodburn P, Omara M, Omoding N, Kizito D, Mpairwe H, Nabulime J, Ameke C, Morison LA & Elliott AM (2007) Associations between mild-to-moderate anaemia in pregnancy and helminth, malaria and HIV infection in Entebbe, Uganda. *Trans R Soc Trop Med Hyg* **101**, 899–907.
34. Geelhoed D, Agadzi F, Visser L, Ablordeppey E, Asare K, O'Rourke P, van Leeuwen JS & van Roosmalen J (2006) Severe anemia in pregnancy in rural Ghana: a case-control study of causes and management. *Acta Obstet Gynecol Scand* **85**, 1165–1171.
35. Chang SC, O'Brien KO, Nathanson MS, Mancini J & Witter FR (2003) Hemoglobin concentrations influence birth outcomes in pregnant African-American adolescents. *J Nutr* **133**, 2348–2355.
36. Malhotra M, Sharma JB, Batra S, Sharma S, Murthy NS & Arora R (2002) Maternal and perinatal outcome in varying degrees of anemia. *Int J Gynaecol Obstet* **79**, 93–100.
37. Murphy JF, O'Riordan J, Newcombe RG, Coles EC & Pearson JF (1986) Relation of haemoglobin levels in first and second trimesters to outcome of pregnancy. *Lancet* **i**, 992–995.
38. Steer PJ (2000) Maternal hemoglobin concentration and birth weight. *Am J Clin Nutr* **71**, 1285S–1287S.
39. Edwards MJ, Novy MJ, Walters CL & Metcalfe J (1968) Improved oxygen release: an adaptation of mature red cells to hypoxia. *J Clin Invest* **47**, 1851–1857.
40. Delpapa EH, Edelstone DI, Milley JR & Balsan M (1992) Effects of chronic maternal anemia on systemic and uteroplacental oxygenation in near-term pregnant sheep. *Am J Obstet Gynecol* **166**, 1007–1012.
41. Richardson BS & Bocking AD (1998) Metabolic and circulatory adaptations to chronic hypoxia in the fetus. *Comp Biochem Physiol A Mol Integr Physiol* **119**, 717–723.
42. Pulgar VM, Zhang J, Massmann GA & Figueroa JP (2006) Prolonged mild hypoxia alters fetal sheep electrocorticogram activity. *J Soc Gynecol Investig* **13**, 404–411.
43. Paulone ME, Edelstone DI & Shedd A (1987) Effects of maternal anemia on uteroplacental and fetal oxidative metabolism in sheep. *Am J Obstet Gynecol* **156**, 230–236.
44. Bocking AD, White SE, Homan J & Richardson BS (1992) Oxygen consumption is maintained in fetal sheep during prolonged hypoxaemia. *J Dev Physiol* **17**, 169–174.
45. Mahajan S, Aalinkeel R, Shah P, Singh S & Kochupillai N (2008) Nutritional anaemia dysregulates endocrine control of fetal growth. *Br J Nutr* **100**, 408–417.
46. Spinillo A, Capuzzo E, Piazzi G, Nicola S, Colonna L & Iasci A (1994) Maternal high-risk factors and severity of growth deficit in small for gestational age infants. *Early Hum Dev* **38**, 35–43.
47. American College of Obstetricians and Gynecologists (2008) ACOG Practice Bulletin No. 95: anemia in pregnancy. *Obstet Gynecol* **112**, 201–207.
48. Jaime-Perez JC, Herrera-Garza JL & Gomez-Almaguer D (2005) Sub-optimal fetal iron acquisition under a maternal environment. *Arch Med Res* **36**, 598–602.
49. Singla PN, Gupta VK & Agarwal KN (1985) Storage iron in human foetal organs. *Acta Paediatr Scand* **74**, 701–706.
50. Andrews NC (2000) Iron homeostasis: insights from genetics and animal models. *Nat Rev Genet* **1**, 208–217.
51. Haskins D, Stevens AR, Finch S & Finch CA (1952) Iron metabolism; iron stores in man as measured by phlebotomy. *J Clin Invest* **31**, 543–547.
52. Barry M (1974) Iron and the liver. *Gut* **15**, 324–334.
53. Gandon Y, Olivie D, Guyader D, Aubé C, Oberti F, Sebille V & Deugnier Y (2004) Non-invasive assessment of hepatic iron stores by MRI. *Lancet* **363**, 357–362.
54. Finch CA, Hegsted M, Kinney TD, Thomas ED, Rath CE, Haskins D, Finch S & Fluharty RG (1950) Iron metabolism; the pathophysiology of iron storage. *Blood* **5**, 983–1008.
55. Finch CA, Bellotti V, Stray S, Lipschitz DA, Cook JD, Pippard MJ & Huebers HA (1986) Plasma ferritin determination as a diagnostic tool. *West J Med* **145**, 657–663.
56. Walters GO, Miller FM & Worwood M (1973) Serum ferritin concentration and iron stores in normal subjects. *J Clin Pathol* **26**, 770–772.
57. Bothwell TH (2000) Iron requirements in pregnancy and strategies to meet them. *Am J Clin Nutr* **72**, 257S–264S.
58. Casanueva E, Pfeffer F, Drijanski A, Fernandez-Gaxiola AC, Gutierrez-Valenzuela V & Rothenberg SJ (2003) Iron and folate status before pregnancy and anemia during pregnancy. *Ann Nutr Metab* **47**, 60–63.
59. Bentley DP (1985) Iron metabolism and anaemia in pregnancy. *Clin Haematol* **14**, 613–628.
60. Milman N, Pedersen NS & Visfeldt J (1983) Serum ferritin in healthy Danes: relation to marrow haemosiderin iron stores. *Dan Med Bull* **30**, 115–120.
61. Hallberg L, Bengtsson C, Lapidus L, Lindstedt G, Lundberg PA & Hulten L (1993) Screening for iron deficiency: an analysis based on bone-marrow examinations and serum ferritin determinations in a population sample of women. *Br J Haematol* **85**, 787–798.

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62. van den Broek NR, Letsky EA, White SA & Shenkin A (1998) Iron status in pregnant women: which measurements are valid? *Br J Haematol* **103**, 817–824.
63. Mor G (2008) Inflammation and pregnancy: the role of toll-like receptors in trophoblast-immune interaction. *Ann N Y Acad Sci* **1127**, 121–128.
64. Brewster JA, Orsi NM, Gopichandran N, McShane P, Ekbote UV & Walker JJ (2008) Gestational effects on host inflammatory response in normal and pre-eclamptic pregnancies. *Eur J Obstet Gynecol Reprod Biol* (Epublication ahead of print version).
65. Rogers JT, Bridges KR, Durmowicz GP, Glass J, Auron PE & Munro HN (1990) Translational control during the acute phase response. Ferritin synthesis in response to interleukin-1. *J Biol Chem* **265**, 14572–14578.
66. Hubel CA, Bodnar LM, Many A, Harger G, Ness RB & Roberts JM (2004) Nonglycosylated ferritin predominates in the circulation of women with preeclampsia but not intrauterine growth restriction. *Clin Chem* **50**, 948–951.
67. Beard JL, Murray-Kolb LE, Rosales FJ, Solomons NW & Angelilli ML (2006) Interpretation of serum ferritin concentrations as indicators of total-body iron stores in survey populations: the role of biomarkers for the acute phase response. *Am J Clin Nutr* **84**, 1498–1505.
68. Thurnham DI, Mburu AS, Mwaniki DL, Muniu EM, Alumasa F & de Wagt A (2008) Using plasma acute-phase protein concentrations to interpret nutritional biomarkers in apparently healthy HIV-1-seropositive Kenyan adults. *Br J Nutr* **100**, 174–182.
69. Khusun H, Yip R, Schultink W & Dillon DH (1999) World Health Organization hemoglobin cut-off points for the detection of anemia are valid for an Indonesian population. *J Nutr* **129**, 1669–1674.
70. Goldenberg RL, Tamura T, DuBard M, Johnston KE, Copper RL & Neggers Y (1996) Plasma ferritin and pregnancy outcome. *Am J Obstet Gynecol* **175**, 1356–1359.
71. Scholl TO (1998) High third-trimester ferritin concentration: associations with very preterm delivery, infection, and maternal nutritional status. *Obstet Gynecol* **92**, 161–166.
72. Xiao R, Sorensen TK, Frederick IO, El-Bastawissi A, King IB, Leisenring WM & Williams MA (2002) Maternal second-trimester serum ferritin concentrations and subsequent risk of preterm delivery. *Paediatr Perinat Epidemiol* **16**, 297–304.
73. Bartha JL, Romero-Carmona R & Comino-Delgado R (2003) Inflammatory cytokines in intrauterine growth retardation. *Acta Obstet Gynecol Scand* **82**, 1099–1102.
74. Makrides M, Crowther CA, Gibson RA, Gibson RS & Skeaff CM (2003) Efficacy and tolerability of low-dose iron supplements during pregnancy: a randomized controlled trial. *Am J Clin Nutr* **78**, 145–153.
75. Conrad ME & Crosby WH (1962) The natural history of iron deficiency induced by phlebotomy. *Blood* **20**, 173–185.
76. Letsky EA (2001) Maternal anaemia in pregnancy. Iron and pregnancy – a haematologists's view. *Fetal Matern Med Rev* **12**, 159–175.
77. Beard JL (2001) Iron biology in immune function, muscle metabolism and neuronal functioning. *J Nutr* **131**, 568S–579S.
78. Maines MD (1981) Zinc protoporphyrin is a selective inhibitor of heme oxygenase activity in the neonatal rat. *Biochim Biophys Acta* **673**, 339–350.
79. Schifman RB, Thomasson JE & Evers JM (1987) Red blood cell zinc protoporphyrin testing for iron-deficiency anemia in pregnancy. *Am J Obstet Gynecol* **157**, 304–307.
80. Romslo I, Haram K, Sagen N & Augensen K (1983) Iron requirement in normal pregnancy as assessed by serum ferritin, serum transferrin saturation and erythrocyte protoporphyrin determinations. *Br J Obstet Gynaecol* **90**, 101–107.
81. Milman N, Ibsen KK & Christensen JM (1987) Serum ferritin and iron status in mothers and newborn infants. *Acta Obstet Gynecol Scand* **66**, 205–211.
82. Hastka J, Lasserre JJ, Schwarzbeck A & Hehlmann R (1994) Central role of zinc protoporphyrin in staging iron deficiency. *Clin Chem* **40**, 768–773.
83. Labbe RF, Vreman HJ & Stevenson DK (1999) Zinc protoporphyrin: A metabolite with a mission. *Clin Chem* **45**, 2060–2072.
84. Lamola AA & Yamane T (1974) Zinc protoporphyrin in the erythrocytes of patients with lead intoxication and iron deficiency anemia. *Science* **186**, 936–938.
85. Kleven KJ, Blohowiak SE & Kling PJ (2007) Zinc protoporphyrin/heme in large-for-gestation newborns. *Neonatology* **92**, 91–95.
86. Brugnara C (2000) Reticulocyte cellular indices: a new approach in the diagnosis of anemias and monitoring of erythropoietic function. *Crit Rev Clin Lab Sci* **37**, 93–130.
87. Thomas C & Thomas L (2002) Biochemical markers and hematologic indices in the diagnosis of functional iron deficiency. *Clin Chem* **48**, 1066–1076.
88. Fishbane S, Galgano C, Langley RC Jr, Canfield W & Maesaka JK (1997) Reticulocyte hemoglobin content in the evaluation of iron status of hemodialysis patients. *Kidney Int* **52**, 217–222.
89. Mast AE, Blinder MA & Dietzen DJ (2008) Reticulocyte hemoglobin content. *Am J Hematol* **83**, 307–310.
90. Mast AE, Blinder MA, Lu Q, Flax S & Dietzen D (2002) Clinical utility of the reticulocyte hemoglobin content in the diagnosis of iron deficiency. *Blood* **99**, 1489–1491.
91. d'Onofrio G, Chirillo R, Zini G, Caenaro G, Tommasi M & Micciulli G (1995) Simultaneous measurement of reticulocyte and red blood cell indices in healthy subjects and patients with microcytic and macrocytic anemia. *Blood* **85**, 818–823.
92. Ervasti M, Kotisaari S, Heinonen S & Punnonen K (2007) Use of advanced red blood cell and reticulocyte indices improves the accuracy in diagnosing iron deficiency in pregnant women at term. *Eur J Haematol* **79**, 539–545.
93. De Domenico I, McVey WD & Kaplan J (2008) Regulation of iron acquisition and storage: consequences for iron-linked disorders. *Nat Rev Mol Cell Biol* **9**, 72–81.
94. Huebers HA & Finch CA (1987) The physiology of transferrin and transferrin receptors. *Physiol Rev* **67**, 520–582.
95. Georgieff MK, Berry SA, Wobken JD & Leibold EA (1999) Increased placental iron regulatory protein-1 expression in diabetic pregnancies complicated by fetal iron deficiency. *Placenta* **20**, 87–93.
96. Li YQ, Yan H & Bai B (2008) Change in iron transporter expression in human term placenta with different maternal iron status. *Eur J Obstet Gynecol Reprod Biol* (Epublication ahead of print version).
97. O'Brien KO, Zavaleta N, Abrams SA & Caulfield LE (2003) Maternal iron status influences iron transfer to the fetus during the third trimester of pregnancy. *Am J Clin Nutr* **77**, 924–930.
98. Halvorsen S (2000) Iron balance between mother and infant during pregnancy and breastfeeding. *Acta Paediatr* **89**, 625–627.
99. McKnight GS, Lee DC, Hemmaplardh D, Finch CA & Palmiter RD (1980) Transferrin gene expression. Effects of nutritional iron deficiency. *J Biol Chem* **255**, 144–147.

https://doi.org/10.1017/S0029665108008732 Published online by Cambridge University Press

100. Malkasian GD Jr, Tauxe WN & Hagedorn AB (1964) Total iron-binding capacity in normal pregnancy. *J Nucl Med* **5**, 243–250.
101. Watkins DK & Butler EB (1966) A micro-method for the determination of serum iron and total iron-binding capacity and its application in pregnancy. *Clin Chim Acta* **13**, 449–456.
102. Morgan EH (1961) Plasma-iron and haemoglobin levels in pregnancy. The effect of oral iron. *Lancet* **i**, 9–12.
103. Nhonoli AM, Kihama FE & Ramji BD (1975) The relation between maternal and cord serum iron levels and its effect on fetal growth in iron deficient mothers without malarial infection. *Br J Obstet Gynaecol* **82**, 467–470.
104. Beaton GH, Corey PN & Steele C (1989) Conceptual and methodological issues regarding the epidemiology of iron deficiency and their implications for studies of the functional consequences of iron deficiency. *Am J Clin Nutr* **50**, 575–585.
105. Hoppe M, Hulthen L & Hallberg L (2003) Serum iron concentration as a tool to measure relative iron absorption from elemental iron powders in man. *Scand J Clin Lab Invest* **63**, 489–496.
106. Knutson MD, Oukka M, Koss LM, Aydemir F & Wessling-Resnick M (2005) Iron release from macrophages after erythrophagocytosis is up-regulated by ferroportin 1 overexpression and down-regulated by hepcidin. *Proc Natl Acad Sci U S A* **102**, 1324–1328.
107. Klausner RD, Rouault TA & Harford JB (1993) Regulating the fate of mRNA: the control of cellular iron metabolism. *Cell* **72**, 19–28.
108. Skikne BS, Flowers CH & Cook JD (1990) Serum transferrin receptor: a quantitative measure of tissue iron deficiency. *Blood* **75**, 1870–1876.
109. Huebers HA & Finch CA (1987) The physiology of transferrin and transferrin receptors. *Physiol Rev* **67**, 520–582.
110. Ferguson BJ, Skikne BS, Simpson KM, Baynes RD & Cook JD (1992) Serum transferrin receptor distinguishes the anemia of chronic disease from iron deficiency anemia. *J Lab Clin Med* **119**, 385–390.
111. Dimitriou H, Stiakaki E, Markaki EA, Bolonaki I, Giannakopoulou C & Kalmanti M (2000) Soluble transferrin receptor levels and soluble transferrin receptor/log ferritin index in the evaluation of erythropoietic status in childhood infections and malignancy. *Acta Paediatr* **89**, 1169–1173.
112. Cook JD, Flowers CH & Skikne BS (2003) The quantitative assessment of body iron. *Blood* **101**, 3359–3364.
113. Robach P, Fulla Y, Westerterp KR & Richalet JP (2004) Comparative response of EPO and soluble transferrin receptor at high altitude. *Med Sci Sports Exerc* **36**, 1493–1498.
114. Metzgeroth G, Adelberger V, Dorn-Beineke A, Kuhn C, Schatz M, Maywald O, Bertsch T, Wisser H, Hehlmann R & Hastka J. (2005) Soluble transferrin receptor and zinc protoporphyrin–competitors or efficient partners? *Eur J Haematol* **75**, 309–317.
115. Choi JW, Im MW & Pai SH (2000) Serum transferrin receptor concentrations during normal pregnancy. *Clin Chem* **46**, 725–727.
116. Akesson A, Bjellerup P, Berglund M, Bremme K & Vahter M (1998) Serum transferrin receptor: a specific marker of iron deficiency in pregnancy. *Am J Clin Nutr* **68**, 1241–1246.
117. Carriaga MT, Skikne BS, Finley B, Cutler B & Cook JD (1991) Serum transferrin receptor for the detection of iron deficiency in pregnancy. *Am J Clin Nutr* **54**, 1077–1081.
118. Herbert V (1987) Making sense of laboratory tests of folate status: folate requirements to sustain normality. *Am J Hematol* **26**, 199–207.
119. Sauberlich HE, Kretsch MJ, Skala JH, Johnson HL & Taylor PC (1987) Folate requirement and metabolism in nonpregnant women. *Am J Clin Nutr* **46**, 1016–1028.
120. Takimoto H, Mito N, Umegaki K, Ishiwaki A, Kusama K, Abe S, Yamawaki M, Fukuoka H, Ohta C & Yoshiike N (2007) Relationship between dietary folate intakes, maternal plasma total homocysteine and B-vitamins during pregnancy and fetal growth in Japan. *Eur J Nutr* **46**, 300–306.
121. Bailey LB (editor) (1995) *Folate in Health and Disease*. New York: Marcel Dekker.
122. Herbert V (1990) Development of human folate deficiency. In *Folic Acid Metabolism in Health and Disease*, pp. 195–210 [MF Picciano, ELR Stokstad and JF Gregory, editors]. New York: Wiley-Liss.
123. Herbert V (1962) Experimental nutritional folate deficiency in man. *Trans Assoc Am Physicians* **75**, 307–320.
124. Wu A, Chanarin I, Slavin G & Levi AJ (1975) Folate deficiency in the alcoholic–its relationship to clinical and haematological abnormalities, liver disease and folate stores. *Br J Haematol* **29**, 469–478.
125. Lurie S (1990) Age distribution of erythrocyte population in late pregnancy. *Gynecol Obstet Invest* **30**, 147–149.
126. Snow CF (1999) Laboratory diagnosis of vitamin B_{12} and folate deficiency: a guide for the primary care physician. *Arch Intern Med* **159**, 1289–1298.
127. Molloy AM & Scott JM (1997) Microbiological assay for serum, plasma, and red cell folate using cryopreserved, microtiter plate method. *Methods Enzymol* **281**, 43–53.
128. Levine S (1993) Analytical inaccuracy for folic acid with a popular commercial vitamin B_{12}/folate kit. *Clin Chem* **39**, 2209–2210.
129. Wright AJ, Finglas PM & Southon S (1998) Erythrocyte folate analysis: a cause for concern? *Clin Chem* **44**, 1886–1891.
130. Wilson DH, Williams G, Herrmann R, Wiesner D & Brookhart P (2005) Issues in immunoassay standardization: the ARCHITECT Folate model for intermethod harmonization. *Clin Chem* **51**, 684–687.
131. Gunter EW, Bowman BA, Caudill SP, Twite DB, Adams MJ & Sampson EJ (1996) Results of an international round robin for serum and whole-blood folate. *Clin Chem* **42**, 1689–1694.
132. Thorpe SJ, Sands D, Heath AB, Hamilton MS, Blackmore S & Barrowcliffe T (2004) An International Standard for whole blood folate: evaluation of a lyophilised haemolysate in an international collaborative study. *Clin Chem Lab Med* **42**, 533–539.
133. Thorpe SJ, Heath A, Blackmore S, Lee A, Hamilton M, O'Broin S, Nelson B & Pfeiffer C (2007) International Standard for serum vitamin B_{12} and serum folate: international collaborative study to evaluate a batch of lyophilised serum for B_{12} and folate content. *Clin Chem Lab Med* **45**, 380–386.
134. Fazili Z, Pfeiffer CM & Zhang M (2007) Comparison of serum folate species analyzed by LC-MS/MS with total folate measured by microbiologic assay and Bio-Rad radioassay. *Clin Chem* **53**, 781–784.
135. Clifford AJ, Noceti EM, Block-Joy A, Block T & Block G (2005) Erythrocyte folate and its response to folic acid supplementation is assay dependent in women. *J Nutr* **135**, 137–143.
136. Pfeiffer CM, Fazili Z, McCoy L, Zhang M & Gunter EW (2004) Determination of folate vitamers in human serum by stable-isotope-dilution tandem mass spectrometry and comparison with radioassay and microbiologic assay. *Clin Chem* **50**, 423–432.

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137. Cole BF, Baron JA, Sandler RS *et al.* (2007) Folic acid for the prevention of colorectal adenomas: a randomized clinical trial. *JAMA* **297**, 2351–2359.
138. Kim YI (2007) Folate and colorectal cancer: an evidence-based critical review. *Mol Nutr Food Res* **51**, 267–292.
139. Gadowsky SL, Gale K, Wolfe SA, Jory J, Gibson R & O'Connor DL (1995) Biochemical folate, B_{12}, and iron status of a group of pregnant adolescents accessed through the public health system in southern Ontario. *J Adolesc Health* **16**, 465–474.
140. Pfeiffer CM, Johnson CL, Jain RB, Yetley EA, Picciano MF, Rader JI, Fisher KD, Mulinare J & Osterloh JD (2007) Trends in blood folate and vitamin B_{12} concentrations in the United States, 1988 2004. *Am J Clin Nutr* **86**, 718–727.
141. McNulty H, Dowey le RC, Strain JJ, Dunne A, Ward M, Molloy AM, McAnena LB, Hughes JP, Hannon-Fletcher M & Scott JM (2006) Riboflavin lowers homocysteine in individuals homozygous for the MTHFR 677C->T polymorphism. *Circulation* **113**, 74–80.
142. Wallace JM, Bonham MP, Strain J *et al.* (2008) Homocysteine concentration, related B vitamins, and betaine in pregnant women recruited to the Seychelles Child Development Study. *Am J Clin Nutr* **87**, 391–397.
143. Refsum H, Nurk E, Smith AD, Ueland PM, Gjesdal CG, Bjelland I, Tverdal A, Tell GS, Nygård O & Vollset SE (2006) The Hordaland Homocysteine Study: a community-based study of homocysteine, its determinants, and associations with disease. *J Nutr* **136**, 1731S–1740S.
144. Thirup P & Ekelund S (1999) Day-to-day, postprandial, and orthostatic variation of total plasma homocysteine. *Clin Chem* **45**, 1280–1283.
145. Jacques PF, Rosenberg IH, Rogers G, Selhub J, Bowman BA, Gunter EW, Wright JD & Johnson CL (1999) Serum total homocysteine concentrations in adolescent and adult Americans: results from the third National Health and Nutrition Examination Survey. *Am J Clin Nutr* **69**, 482–489.
146. Pentieva K, McNulty H, Reichert R *et al.* (2004) The short-term bioavailabilities of [6S]-5-methyltetrahydrofolate and folic acid are equivalent in men. *J Nutr* **134**, 580–585.
147. Cikot RJ, Steegers-Theunissen RP, Thomas CM, de Boo TM, Merkus HM & Steegers EA (2001) Longitudinal vitamin and homocysteine levels in normal pregnancy. *Br J Nutr* **85**, 49–58.
148. Murphy MM, Scott JM, McPartlin JM & Fernandez-Ballart JD (2002) The pregnancy-related decrease in fasting plasma homocysteine is not explained by folic acid supplementation, hemodilution, or a decrease in albumin in a longitudinal study. *Am J Clin Nutr* **76**, 614–619.
149. Roopnarinesingh R, Jackson B, Osman Z, Harrison R & Mayne P (2006) Homocysteine in assisted reproduction: does oestradiol influence homocysteine levels? *J Obstet Gynaecol* **26**, 59–62.
150. Refsum H, Smith AD, Ueland PM *et al.* (2004) Facts and recommendations about total homocysteine determinations: an expert opinion. *Clin Chem* **50**, 3–32.
151. Grubben MJ, Boers GH, Blom HJ, Broekhuizen R, de Jong R, van Rijt L, de Ruijter E, Swinkels DW, Nagengast FM & Katan MB (2000) Unfiltered coffee increases plasma homocysteine concentrations in healthy volunteers: a randomized trial. *Am J Clin Nutr* **71**, 480–484.
152. McPartlin J, Courtney G, McNulty H, Weir D & Scott J (1992) The quantitative analysis of endogenous folate catabolites in human urine. *Anal Biochem* **206**, 256–261.
153. McNulty H, McPartlin J, Weir D & Scott J (1993) Reversed-phase high-performance liquid chromatographic method for the quantitation of endogenous folate catabolites in rat urine. *J Chromatogr* **614**, 59–66.
154. Sokoro AA, Etter ML, Lepage J, Weist B, Eichhorst J & Lehotay DC (2006) Simple method for the quantitative analysis of endogenous folate catabolites p-aminobenzoylglutamate (pABG) and its acetamido (apABG) derivative in human serum and urine by liquid chromatography-tandem mass spectrometry. *J Chromatogr B Analyt Technol Biomed Life Sci* **832**, 9–16.
155. Hannisdal R, Svardal A & Ueland PM (2008) Measurement of folate in fresh and archival serum samples as p-aminobenzoylglutamate equivalents. *Clin Chem* **54**, 665–672.
156. Gregory JF III, Caudill MA, Opalko FJ & Bailey LB (2001) Kinetics of folate turnover in pregnant women (second trimester) and nonpregnant controls during folic acid supplementation: stable-isotopic labeling of plasma folate, urinary folate and folate catabolites shows subtle effects of pregnancy on turnover of folate pools. *J Nutr* **131**, 1928–1937.
157. Baker H, Frank O, Deangelis B, Feingold S & Kaminetzky HA (1981) Role of placenta in maternal-fetal vitamin transfer in humans. *Am J Obstet Gynecol* **141**, 792–796.
158. Vollset SE, Refsum H, Irgens LM, Emblem BM, Tverdal A, Gjessing HK, Monsen AL & Ueland PM (2000) Plasma total homocysteine, pregnancy complications, and adverse pregnancy outcomes: the Hordaland Homocysteine study. *Am J Clin Nutr* **71**, 962–968.
159. Ray JG & Laskin CA (1999) Folic acid and homocyst(e)ine metabolic defects and the risk of placental abruption, pre-eclampsia and spontaneous pregnancy loss: A systematic review. *Placenta* **20**, 519–529.
160. Nelen WL, Blom HJ, Steegers EA, den HM & Eskes TK (2000) Hyperhomocysteinemia and recurrent early pregnancy loss: a meta-analysis. *Fertil Steril* **74**, 1196–1199.
161. Scholl TO, Hediger ML, Schall JI, Khoo CS & Fischer RL (1996) Dietary and serum folate: their influence on the outcome of pregnancy. *Am J Clin Nutr* **63**, 520–525.
162. Kosmas IP, Tatsioni A & Ioannidis JP (2004) Association of C677T polymorphism in the methylenetetrahydrofolate reductase gene with hypertension in pregnancy and pre-eclampsia: a meta-analysis. *J Hypertens* **22**, 1655–1662.
163. MRC Vitamin Study Research Group (1991) Prevention of neural tube defects: results of the Medical Research Council Vitamin Study. *Lancet* **338**, 131–137.
164. Czeizel AE & Dudas I (1992) Prevention of the first occurrence of neural-tube defects by periconceptional vitamin supplementation. *N Engl J Med* **327**, 1832–1835.
165. Adams JF, Tankel HI & MacEwan F (1970) Estimation of the total body vitamin B_{12} in the live subject. *Clin Sci* **39**, 107–113.
166. Boddy K & Adams JF (1972) The long-term relationship between serum vitamin B_{12} and total body vitamin B_{12}. *Am J Clin Nutr* **25**, 395–400.
167. Metz J, McGrath K, Bennett M, Hyland K & Bottiglieri T (1995) Biochemical indices of vitamin B_{12} nutrition in pregnant patients with subnormal serum vitamin B_{12} levels. *Am J Hematol* **48**, 251–255.
168. Pardo J, Peled Y, Bar J, Hod M, Sela BA, Rafael ZB & Orvieto R (2000) Evaluation of low serum vitamin B_{12} in the non-anaemic pregnant patient. *Hum Reprod* **15**, 224–226.
169. Koebnick C, Heins UA, Dagnelie PC, Wickramasinghe SN, Ratnayaka ID, Hothorn T, Pfahlberc AB, Hoffmann I, Lindemans J & Leitzmann C (2002) Longitudinal concentrations of vitamin B_{12} and vitamin B_{12}-binding proteins during uncomplicated pregnancy. *Clin Chem* **48**, 928–933.

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170. Allen RH, Stabler SP, Savage DG & Lindenbaum J (1990) Diagnosis of cobalamin deficiency I: Usefulness of serum methylmalonic acid and total homocysteine concentrations. *Am J Hematol* **34**, 90–98.
171. Lindenbaum J, Savage DG, Stabler SP & Allen RH (1990) Diagnosis of cobalamin deficiency: II. Relative sensitivities of serum cobalamin, methylmalonic acid, and total homocysteine concentrations. *Am J Hematol* **34**, 99–107.
172. Obeid R, Morkbak AL, Munz W, Nexo E & Herrmann W (2006) The cobalamin-binding proteins transcobalamin and haptocorrin in maternal and cord blood sera at birth. *Clin Chem* **52**, 263–269.
173. Refsum H, Yajnik CS, Gadkari M *et al.* (2001) Hyperhomocysteinemia and elevated methylmalonic acid indicate a high prevalence of cobalamin deficiency in Asian Indians. *Am J Clin Nutr* **74**, 233–241.
174. Bondevik GT, Schneede J, Refsum H, Lie RT, Ulstein M & Kvale G (2001) Homocysteine and methylmalonic acid levels in pregnant Nepali women. Should cobalamin supplementation be considered? *Eur J Clin Nutr* **55**, 856–864.
175. Yajnik CS, Deshpande SS, Panchanadikar AV, Naik SS, Deshpande JA, Coyaji KJ, Fall C & Refsum H (2005) Maternal total homocysteine concentration and neonatal size in India. *Asia Pac J Clin Nutr* **14**, 179–181.
176. Muthayya S, Dwarkanath P, Mhaskar M, Mhaskar R, Thomas A, Duggan C, Fawzi WW, Bhat S, Vaz M & Kurpad A (2006) The relationship of neonatal serum vitamin B_{12} status with birth weight. *Asia Pac J Clin Nutr* **15**, 538–543.

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