Maternal Inositol Status and Neural Tube Defects: A Role for the Human Yolk Sac in Embryonic Inositol Delivery?

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ABSTRACT

Supplementation with myo-inositol during the periconceptional period of pregnancy may ameliorate the recurrence risk of having a fetus affected by a neural tube defect (NTD; e.g., spina bifida). This could be of particular importance in providing a means for preventing NTDs that are unresponsive to folic acid. This review highlights the characteristics of inositol and describes the role of myo-inositol in the prevention of NTDs in rodent studies and the evidence for its efficacy in reducing NTD risk in human pregnancy. The possible reduction in NTD risk by maternal myo-inositol implies functional and developmentally important maternal–embryonic inositol interrelationships and also suggests that embryonic uptake of myo-inositol is crucial for embryonic development. The establishment of active myo-inositol cellular uptake mechanisms in the embryonic stages of human pregnancy, when the neural tube is closing, is likely to be an important determinant of normal development. We draw attention to the generation of materno-fetal inositol concentration gradients and relationships, and outline a transport pathway by which myo-inositol may be delivered to the early developing human embryo. These considerations provide novel insights into the mechanisms that may underpin inositol’s ability to confer embryonic developmental benefit.

Introduction

Inositol is present in a variety of foods including nuts, seeds, vegetables and fruit, with myo-inositol (Figure 1) being the predominant isomeric form (1). Inositol may exist as free myo-inositol, myo-inositol–containing phospholipids (phosphoinositides), or as phytic acid (inositol hexakisphosphate), which is hydrolyzed mostly to free inositol before absorption from the gut (1, 2). Myo-inositol is a sugar alcohol referred to as a “cyclitol” or “polyol” due to its cyclic structure containing 6 hydroxyl groups (Figure 1). The differing spatial orientation of its 6 hydroxyl groups gives rise to 9 stereoisomeric inositol forms (1, 3). Adults typically consume 1 g of myo-inositol/d (1–5). In addition, most tissues are able to produce myo-inositol endogenously (~4 g/d) (1, 3) from α-glucose by de novo synthesis involving the following: 1) phosphorylation of glucose by hexokinase to glucose 6-phosphate, 2) conversion of glucose 6-phosphate to myo-inositol-1-phosphate by 1-deoxyinositol-phosphate synthase (encoded by ISYNA1 gene) (6, 7), and 3) dephosphorylation of inositol-1-phosphate by inositol monophosphatase to generate free myo-inositol (Figure 1) (1, 4, 8).

Myo-inositol is the predominant inositol stereoisomer in mammalian cells (1, 3, 5, 9). The plasma concentration of myo-inositol in healthy adults is ~30 μmol/L, which is thought to reflect the balance of dietary inositol intake, cellular uptake by Na+- and energy-dependent...
FIGURE 1  Myo-inositol biosynthesis and catabolism in mammalian tissues. Most tissues can synthesize myo-inositol following phosphorylation of D-glucose to glucose-6-phosphate with subsequent synthesis of myo-inositol-1-phosphate, which, following dephosphorylation, forms free myo-inositol. This can be incorporated into the phosphoinositides cycle, be further catabolized to D-glucuronate for renal excretion or, following a series of enzymatic reactions, be converted back to glucose-6-phosphate. Additionally, myo-inositol can be converted to D-chiro-inositol through the enzymatic action of an epimerase.

co-transporters distributed to several tissues (10–12), endogenous synthesis from glucose, cellular metabolism, and clearance (3, 5, 13, 14). Myo-inositol clearance is accompanied by catabolism of myo-inositol by myo-inositol oxygenase (MIOX) to D-glucuronate followed by renal excretion (1, 3, 8, 15) (Figure 1). Myo-inositol can also be converted to D-chiro-inositol by an epimerization catalytic step (Figure 1), although the conversion rate is relatively low (1, 4).

This review integrates current concepts regarding the importance of myo-inositol in embryonic development, its efficacy in reducing the risk of neural tube defects
(NTDs), materno-fetal inositol relationships, and the role of inositol transporters in embryonic/fetal myo-inositol provision.

**Inositol, Early Embryonic Development, and Neural Tube Closure**

As early as preimplantation stages of mammalian development there is a notable requirement for myo-inositol, with uptake increasing from the 1-cell to the blastocyst stage; myo-inositol incorporation into the phosphatidylinositol cycle promotes cell proliferation (16–19). Mouse embryos exposed to myo-inositol in vitro display an increase in proliferative activity and a faster cleavage rate resulting in more blastocysts (20, 21). Hence myo-inositol transporters must be active over this period of preimplantation development to meet myo-inositol demand if this cannot be met by endogenous production. Indeed, in the mouse preimplantation embryo, myo-inositol uptake appears to involve mainly Na<sup>+</sup>-dependent inositol transporters with a minor contribution from Na<sup>+</sup>-independent mechanisms (18). Early developmental induction of carrier-mediated transporters also has relevance for the progressive growth of the embryo and fetus at postimplantation stages, as neural tissues contain high concentrations of myo-inositol, achieved through active transport of myo-inositol (3).

Studies in rodent embryos have shown that inositol deficiency results in cranial NTDs in cultured embryos (22–24), indicating a crucial role for inositol in neural tube closure. Inositol supplementation is effective in reducing embryopathy, including NTDs associated with hyperglycemia, diabetes, and folate deficiency (4). Neural tube closure is particularly sensitive to inositol status in the curly tail mouse strain, a multigenic model in which the major gene defect is a hypomorphic allele of the grainyhead-like transcription factor 3 gene (Grhl3) (25). NTDs in curly tail mutants are unresponsive to prevention by folic acid (or methionine), but in contrast, inositol supplementation reduces the incidence of spina bifida (4, 26), an effect that can be mediated by either myo- or D-chiro-inositol. Each stereoisomer reduces the incidence of spina bifida in a dose-dependent manner, inferring that both forms of inositol can be taken up by the embryo (27). The mechanism underlying the higher preventive capacity of D-chiro-inositol as compared with myo-inositol is not currently understood (27). Stimulation of protein kinase C (PKC) activity, specifically of the β1 and γ isoforms, with a lesser contribution from PKCζ, contributes to the ameliorating effects of myo-inositol on impaired neural tube closure (26, 28). It has been speculated that the enhanced protective effect of D-chiro-inositol could be by eliciting greater downstream effects on PKC activation (27).

These observations suggest there must be a pathway available for delivery of maternal myo-inositol (or derived active inositol metabolites) to the developing embryo during pregnancy, when neural tube closure occurs. Defining the embryonic inositol pathway will be an important determinant for future myo-inositol–focused therapeutic strategies, informed by an understanding of materno-fetal myo-inositol interrelationships and mechanisms driving embryonic/fetal delivery.

**Materno-Fetal Inositol Relationships**

Lower serum myo-inositol concentrations have been reported in mothers of children with spina bifida (29), suggesting a possible predisposing association as found in animal models. Whether myo-inositol synthesis might be altered in NTDs has not been determined. The ISYNA1 gene is expressed in adult human tissues as well as in placenta and yolk sac (7, 30), leading to the hypothesis that genetic defects of myo-inositol synthase may result in low maternal and/or embryonic intracellular myo-inositol concentrations, predisposing to NTD pathogenesis (31). In a case-control triad study of children with spina bifida aged 1 to 3 y and their parents, genetic defects of the ISYNA1 gene were investigated but no association with spina bifida was noted (31).

A higher fetal inositol concentration relative to maternal exists in several species (32). Indeed, in the early weeks of human pregnancy (5–12 wk), inositol concentration in the embryonic compartment is already significantly higher than in maternal serum (33), suggesting that active, carrier-mediated transport mechanisms for inositol are established early in pregnancy and/or there is substantial placental/fetal production of inositol. In matched samples of human intervillous, coelomic, and amniotic fluids, taken over this gestational period, the concentration of inositol in each fluid was significantly higher than that in maternal serum (33). The concentration of inositol in the coelomic fluid that bathes the yolk sac within the exocoelomic cavity (Figure 2) was particularly high, reported to be ~10-fold higher than maternal serum (33). The high myo-inositol tissue concentrations in the developing central nervous system (CNS), skeletal, and cardiac muscle (34) emphasize the high embryonic demand for this nutrient. Myo-inositol, along with other polyols, may have multiple functions during embryogenesis, acting as osmolytes to promote expansion of the amniotic and coelomic cavities, providing precursors of cell membrane components and supplying substrates for the pentose phosphate pathway necessary for the synthesis of nucleic acids (33). Moreover, the high concentration of polyols, including sorbitol, in the embryonic compartment may reflect an early dependence on polyol metabolic pathways that serve to maintain ATP concentrations and redox potential while the embryo develops in a low oxygen environment (33).

The high early pregnancy demand for myo-inositol is also reflected in rodent pregnancy, as suggested by the decline in total fetal inositol content as pregnancy advances (35). This phenomenon may also be related to altered placental de novo synthesis of myo-inositol, as evidenced by the decline in human pregnancy of umbilical venous concentration between midgestation and term (36). By midgestation of human pregnancy, umbilical venous myo-inositol concentration is higher than maternal (~6-fold) (36), and later, in newborn infants at term, umbilical venous myo-inositol concentration is ~4-fold higher than in maternal blood (37, 38). Neonatal
myo-inositol concentrations gradually decline over the first few months after birth to attain concentrations comparable to adults (38).

Fetal production of myo-inositol is also likely based on the evidence that umbilical arterial blood returning to the placenta has a significantly higher myo-inositol concentration than that in umbilical venous blood (36, 37), generating a negative umbilical venous-arterial concentration difference for myo-inositol that is not seen for other polyols (37). Staat et al. (39) infused stable isotope–labeled inositol into mothers 2 h before delivery and demonstrated that the plasma enrichment ratio of fetal (cord)/maternal tracer concentration deviated markedly from the value of 1, interpreted as inositol in the fetal circulation not being directly dependent on maternal inositol concentration. Although a higher fetal inositol concentration was achieved, this did not appear to be all maternally derived, with a fetal/maternal isotopic enrichment ratio of fetal (cord)/maternal tracer concentration of 0.12, suggesting that only ~12% of fetal inositol originated from maternal plasma. However, the 2-h period of this study was considered to be a potential limitation, such that dilution by placenta-derived inositol (36, 37) is also a possibility.

Myo-inositol is transported by 3 different transporters: the lower affinity H\(^+\)-coupled inositol transporter (HMIT) (41), and two higher affinity Na\(^+\)-dependent myo-inositol transporters (SMIT), called SMIT1 (42, 43) and SMIT2 (44), members of the solute carrier SLC5 gene family of Na\(^+\)-dependent glucose co-transporters (45). SMIT1 and SMIT2 react to osmotic imbalances (46–48), whereas no major osmoregulatory function has been reported for HMIT. Despite their common inositol transporting ability, it is worth noting that these transporters do not share amino acid sequence homology (41, 49).

HMIT
Activity of HMIT, encoded by SLC2A13, is stimulated by an inwardly directed H\(^+\)-gradient through an increase in maximal velocity (\(V_{\text{max}}\)) with no change in substrate affinity (\(K_m \sim 100 \mu M\) for myo-inositol) (41). HMIT is predominantly expressed in the brain, with greatest abundance in the hippocampus, hypothalamus, cerebellum, and brain stem, although it is also expressed in other tissues such as the kidney (41, 50). The HMIT protein shows the same membrane topology as other SLC2 glucose transporter (GLUT) family members, and hence its designation as GLUT13, comprising 12 transmembrane domains, an enlarged loop
between the sixth and seventh transmembrane domain, and N- and C-termini located within the cytoplasm. In addition, it possesses an extracellular loop between the ninth and tenth transmembrane domains (41, 49, 50). HMIT is generally localized to intracytoplasmic membranes (50), and in neurons is located to the Golgi apparatus (51) and plasma membrane (41). Scylla-, D-chiro-, and myo-inositol are also accepted as substrates, but glucose, fructose, and other hexoses are not (41). HMIT activity can, however, be reduced by common GLUT inhibitors such as phlorizin and phloretin (41). Recently, it has been proposed that HMIT mediates the transport of inositol triphosphate (IP3) and, in doing so, may play a role in the intracellular regulation of phosphoinositide signaling (51).

**SMIT1**

The Na⁺/myo-inositol co-transporter SMIT1, encoded by *SLC5A3* (42), has a role in cellular adaptation to hypertonicity (46, 47) by accumulating myo-inositol, particularly in the kidney and brain (49). It has a similar tissue distribution pattern to SMIT2, being expressed in the kidney, heart, skeletal muscle, placenta, and brain, although, in the CNS, SMIT1 has a relatively high expression (49, 52, 53). The preferred substrate for SMIT1 is myo-inositol (K_m = 55 μM) and its transport of fucose allows its activity to be distinguished from that of SMIT2 (49). The human *SLC5A3* gene has been proposed to give rise to mRNA splice variants: one that encodes the SMIT1 protein containing 14 transmembrane helices and two other variants SMIT1-2 and SMIT1-3 that encode SMIT1 isoforms with different C-termini but without the last transmembrane domain (49).

Mice homozygous null for *Slc5a3* exhibit a 77% reduction in myo-inositol content by embryonic day (E) 10.5, which is still evident at late fetal stages, with an 84% reduction reported at E18.5 (35). No histological defects of the placenta or a variety of other fetal tissues were noted (35). Offspring are reported as having a normal weight and gross appearance at birth (35), while other reports state that newborns have a small body size, short limbs, drooped forelimbs and a curved spine as compared with wild-type mice (54). Notwithstanding these discrepancies, a consistent observation is that *Slc5a3*-null mice die shortly after birth, apparently due to neurological dysfunction, cyanosis, and hypoventilation (35, 55). Despite the severely diminished myo-inositol content of the fetal forebrain of *Slc5a3* homozygous null mutants (35), brain phosphoinositide concentrations were not altered in the fetus (56, 57).

Interestingly, the survival and viability of *Slc5a3*-null fetuses could be rescued by enriching drinking water of pregnant dams with 1% (54, 55, 57) or 2% (58) myo-inositol. Supplementation maternal myo-inositol intake between days E9.5 and E15.5 in mice was found to be a crucial gestational window for phenotypic rescue (55). However, surviving myo-inositol-supplemented *Slc5a3* knockout offspring still exhibited myo-inositol depletion in the brain, kidney, and skeletal muscle. This was associated with severe abnormalities of the peripheral nerves—in particular, the sciatic nerve—and bones with delayed prenatal skeletal mineralization, diminished postnatal bone density, and altered bone remodeling (55, 57, 58). Together, these phenomena confirm the importance of SMIT1 transporter activity during fetal development and its crucial contribution to fetal myo-inositol accretion, but also infer that compensatory SMIT1-independent mechanisms are able to prevent neonatal lethality and restore offspring viability following maternal inositol supplementation. However, these activities failed to fully restore fetal or offspring tissue myo-inositol concentrations in surviving mutants.

**SMIT2**

SMIT2 is encoded by *SLC5A11* (also called KST1) and is 43% identical in nucleotide sequence to SMIT1 (44). SMIT2 is expressed in human heart, skeletal muscle, kidney, liver, and placenta, and more weakly in the brain (59). SMIT2 transport of myo-inositol is Na⁺-dependent with a K_m of 120 μM. SMIT2 is inhibited by phlorizin and exhibits stereospecific cotransport of both D-glucose and D-xylose but does not transport fucose (which is transported by SMIT1) (49). SMIT2 also transports D-chiro-inositol (K_m = 130 μM), with similar affinity to myo-inositol. In contrast, D-chiro-inositol is not transported by SMIT1, allowing distinction between the two transporters (49). The physiological substrate of SMIT2 is postulated to be myo-inositol as plasma D-chiro-inositol concentrations are low (49). In humans, a lower serum myo-inositol concentration was found in mothers with the *SLC5A11* CC genotype compared with the TT genotype, although there was no association between this genetic polymorphism and spina bifida (31).

Schneider (49) draws attention to the co-expression of SMIT1 and SMIT2 in several tissues, which may influence the kinetics of inositol transport depending on their relative contributions (44). In the curly tail (folic acid–unresponsive) mouse, D-chiro-inositol is more effective than myo-inositol in the prevention of NTDs (27), suggesting that SMIT2-mediated inositol uptake activity is pivotal in eliciting such downstream preventive responses. In clinical studies, the efficacy of D-chiro-inositol in combination with myo-inositol has been reported in the treatment of polycystic ovarian syndrome (60) and gestational diabetes (61). D-chiro- and myo-inositol could be beneficial based on the relatively high myo-inositol concentrations reported in reproductive organs compared with blood (62) and the insulin-sensitizing properties of these inositol stereoisomers in experimental models of hyperglycemia and diabetes (1).

Together, these studies highlight the importance of myo-inositol provision during gestational development and imply the existence of maternal–fetal inositol transfer pathways that confer embryonic developmental benefits, potentially including NTD prevention. This concept is strengthened by the following collective observations:

1) Myo-inositol supplementation prevents the reduced myo-inositol content and NTDs induced in cultured rat...
conceptuses by hyperglycemia, suggesting that myo-inositol depletion is involved in diabetic embryopathy (63, 64). Tissue myo-inositol concentration of fetuses with a NTD phenotype was more profoundly diminished than in unaffected fetuses of diabetic rat dams. Additionally, reduced yolk sac inositol tissue concentration in the diabetic group was restored to control concentrations with maternal inositol supplementation (65).

2) An inositol-sensitive developmental pathway is suggested from inositol supplementation studies showing reduced incidence of NTDs in mouse models (24).

3) Myo-inositol uptake into mouse blastocysts is mediated by a Na+-dependent, temperature-sensitive mechanism, which can be inhibited by raised glucose concentrations (13), suggesting an importance for myo-inositol as early as the blastocyst stage (16).

4) The high inositol concentration in coelomic fluid in direct contact with the human yolk sac (Figure 2), during early pregnancy and organogenesis phases of embryonic development, is likely to contribute to the maintenance of inositol metabolic pathways that promote optimal embryonic growth and development (33).

A Role for the Placenta and Yolk Sac in Embryonic/Fetal Inositol Delivery?

As well as supporting evidence for the existence of functional carrier-mediated myo-inositol uptake mechanisms in early embryonic development, additional studies draw attention to the potential capacity of the placenta and yolk sac as a site of myo-inositol uptake and/or myo-inositol synthesis. In early human pregnancy, when the neural tube and other embryonic organ systems are forming, blood flow through the utero-placental circulation has yet to be initiated. Maternal blood flow to the maternal spiral artery openings of the placenta is initially occluded by plugs of migrating endovascular trophoblast cells (66, 67) (Figure 2). The functional advantage of this arrangement is that blood flow is minimized so that the embryo can undergo organogenesis in a low oxygen environment, which may limit the potential of any damaging effect of reactive oxygen species (67, 68). Hence, the spiral artery openings remain plugged over most of the duration of the first trimester (when embryonic organogenesis is occurring) and it is the diffuse network of intercellular spaces forged between the amased endovascular trophoblast cells that provides the direct link between the arterial lumen of the spiral arteries and the intervillous space surrounding the chorionic (placental) villi (69–71). The intervillous space contains a colorless fluid thought to consist of a mixture of maternal plasma that has percolated through the network of intercellular channels between the trophoblast cells, and carbohydrate- and lipid-rich secretions ("histiotrophic") from the maternal uterine glands that transit directly to the intervillous space (66, 67) (Figure 2). Nutrients contained therein are proposed to be taken up by the epithelial syncytiotrophoblast layer of the placental villi (66, 67, 72, 73). Towards the end of the first trimester, at ~10 wk of gestation, the trophoblast cell “plugs” start to loosen, allowing the maternal arterial circulation to flow to the intervillous space with the ensuing full establishment of the utero-placental circulation in concert with contemporaneous elaboration of the feto-placental circulation (67, 71).

Hence, during critical periods of human development, transfer of nutrients and precursors for embryonic development and growth occurs prior to the onset of established blood flow through the placental circulation. This poses a very interesting question: How is delivery of maternal nutrients, including myo-inositol, that are essential for embryonic development and growth, achieved over this very vulnerable period of developmental embryogenesis when the neural tube is closing? Although not well defined, the current proposition is that maternal–embryonic nutrient transfer is mediated by the mode of nutrition known as "histiotrophic" nutrition (74), as illustrated in Figure 2. In this scheme, the yolk sac is likely to have a crucial role in the provision of embryonic nutrition (74) as it is 1) connected directly to the developing embryo by the vitelline circulation (71, 74) and 2) connected by the vitelline duct to the embryonic gut (75). The latter anatomical connection remains patent until ~8–9 wk of fetal life when it is obliterated (75). Because the yolk sac exists only to ~12 wk of human pregnancy (76), it has remained elusive from investigation. In this context, the rodent visceral yolk sac, which persists throughout pregnancy and is readily accessible as an outer membrane that envelops the fetus, becomes a useful surrogate for study, particularly as it known that the yolk sacs of both species express common transport moieties and receptors, such as folate receptor α, cubulin, and megalin (77–80). Additionally, the rodent yolk sac is well known to contribute to embryonic nutrition (81, 82).

At term, the human placenta expresses the SLC5A3 and SLC5A11 genes encoding SMIT1 (53) and SMIT2 (59) myo-inositol transporters, respectively. However, expression in early pregnancy has not been examined. In a preliminary study, we investigated the expression of inositol transporters in pooled cDNA from 30 first-trimester placentas using gene-specific primers to each of the three myo-inositol transporters and confirmed the expression of the SLC5A3 and SLC5A11 genes. Additionally, we detected the placental expression of SLC2A13 transcripts encoding HMIT, showing that all three genes are expressed in first-trimester placentas matched to first-trimester placentas from the same pregnancies. The expression of all three inositol transporter genes was confirmed in human yolk sac (unpublished data; N Sardena and J Glazier, 2018). We hypothesized that, within the setting of a high inositol concentration in coelomic fluid that is in direct contact with the yolk sac’s outer surface (33), the human yolk sac would also express these three inositol transporters, in common with the placenta. To test this hypothesis, we examined SLC2A13, SLC5A3, and SLC5A11 gene expression in human yolk sacs, matched to first-trimester placentas from the same pregnancies. The expression of all three inositol transporter genes was confirmed in human yolk sac (unpublished data; N Sardena and J Glazier, 2018). This is in partial agreement with recent analysis of the human yolk sac transcriptome (30), which also identified SLC2A13 (HMIT) and SLC5A11 (SMIT2) transcripts, although the expression
of SLC5A3 (SMIT1) transcripts was not reported in that study (30).

Hence, our findings identify for the first time the co-
expression of all three inositol transporters in the first-
trimester human placenta and pregnancy-matched yolk sacs. This raises the possibility that these three transporters may be involved in carrier-mediated uptake of myo-inositol and play a role in embryonic inositol provision and developmental pathways dependent on myo-inositol availability. Further functional studies are required to test this postulate and to characterize the pathways involved that might underpin the delivery of maternally derived myo-inositol to the developing embryo at critical developmental time points. It is possible, by analogy to other cell types that HMIT- and SMIT-mediated activities may each contribute to cellular myo-inositol uptake under different prevailing conditions.

It is rather difficult to reconcile the concepts that mater-
nally derived myo-inositol does not impact on embryo/fetal inositol, when maternal myo-inositol supplementation confers embryological benefits, unless maternal myo-inositol drives downstream metabolic signaling events that have a direct influence. Hence, an improved understanding of cellular myo-inositol transport and uptake mechanisms provides a mechanistic framework to delineate how inositol might exert beneficial effects.

**Inositol and Pleiotropic Effects**

In the E10.5 rat conceptus (10–12 somites), cellular uptake of myo-inositol and accumulation into the tissue pool and lipid components were inhibited competitively by increasing concentrations of D-glucose, an effect not observed with other hexoses (83). In diabetic mothers, cellular depletion of myo-inositol might therefore contribute to the associated increased risk of birth defects, including NTDs (84). Indeed, a variety of models of diabetic complications exhibit intracel-
ular depletion of myo-inositol (85). Further, there is evidence supporting a possible role of myo-inositol supplementation in reducing the incidence of diabetic embryopathy, including NTDs (4, 86–88). These outcomes have stimulated interest in the pleiotropic effects of inositol with regard to the following: 1) the insulin-mimetic effects of myo-inositol (1), 2) generation of inositol phosphoglycan signaling molecules from glycosyolphosphatidylinositol membrane anchoring moieties (89), 3) the role of intracellular myo-inositol as an organic osmolyte (90, 91), and 4) involvement in signaling pathways through generation of IP3, phosphatidyli-
nositol phosphate lipids [phosphatidylinositol bisphosphate (PIP2)/phosphatidylinositol triphosphate (PIP3)], and other derivatives (92–95). These multiple physiological actions of inositol have led to several clinical studies investigating whether myo-inositol or D-chiro-inositol may be effective in prophylaxis and treatment of diabetes or gestational diabetes (96, 97), and have also initiated assessment of whether maternal myo-inositol supplementation in the periconceptional period might be effective in reducing NTD risk (4, 85).

**Folate, Inositol, and NTDs—Evidence for Folate-Sensitive and Inositol-Sensitive Etiologies**

By the fourth week postconception, the embryonic neural plate has undergone a series of coordinated morphological events culminating in the formation of the closed neural tube (98, 99). Failure of the processes underpinning neural tube closure leads to NTDs, including anencephaly and spina bifida (98–100). These are among the most serious congenital malformations of the CNS, with a prevalence worldwide of 0.5–2.0 per 1000 established pregnancies (101) and 0.9 per 1000 births in Europe (102–104). Prenatal screening has led to early detection and termination of NTD-affected pregnancies, resulting in lower NTD-affected birth rates in some countries (105, 106). Women with ≥1 previous pregnancies associated with NTDs have a higher risk of a subsequent affected pregnancy (107). The recurrence risk after a single affected pregnancy of 3.2% increases to 11.8% after two affected pregnancies (107). Patterns of inheritance indicate a major genetic contribution to NTD risk (99, 108, 109). Yet, it is also well recognized that maternal nutrition has an important role in influencing NTD prevalence, with interplay between genetic variants and nutritional factors contributing to NTD risk (99).

This has led to a sustained interest in elucidating how maternal nutritional intake may impact NTD risk. Given the evidence that the risk of having a NTD-affected pregnancy is increased by low maternal blood folate concentrations (99, 110–112), focus has centered on the effects of maternal B vitamins such as folate and vitamin B-12, with one-carbon metabolism and methylation postulated to be cellular loci that can be modulated by these nutrients to influence NTD risk (100, 113).

However, although an inverse relation between maternal folate concentration and NTD risk prevails (114, 115), the range of maternal blood folate concentrations determined in affected cases rarely indicates clinical folate deficiency (99). Moreover, the intake of folic acid supplements used preconception reduces the risk of NTD occurrence and recurrence but does not prevent all cases (116). A randomized trial (116) reported that the 3.6% of NTD recurrence with no folic acid fell to 0.6% with folic acid supplements. The efficacy of folic acid has been replicated in a series of further intervention trials (112), with compelling evidence that maternal intake of folic acid supplements in the periconceptional period significantly reduces NTD risk (117), with prevention also achieved by folic acid fortification of flour (118). Clinical case studies have therefore drawn attention to a subset of NTDs (~30%) referred to as “folic acid resistant” NTDs (4, 119, 120) that occur despite the use of folic acid in the periconceptional period.

Research in the *curly tail* (*Grhl3*) mouse mutant demonstrated a preventive effect of inositol on NTDs that are resistant to folic acid supplementation (4, 26). Further, a lower maternal myo-inositol concentration in humans is associated with a greater risk of having a spina
bifida–affected infant (29). Such observations led to the use of myo-inositol in a highly selected group of women to prevent NTD recurrence in a subsequent pregnancy (119–121). A cohort of 12 women with a history of folic acid–resistant NTDs, who were counseled to take a combination of myo-inositol and folic acid supplements before a subsequent pregnancy, gave birth to healthy infants without NTDs (119–121). While the number of study participants was too small to draw firm conclusions, the findings encouraged the view that myo-inositol may contribute towards NTD prevention, advocating the need for a more fully powered study (4).

Progressing this concept, a pilot double-blind clinical trial assessed whether the use of inositol supplements in combination with folic acid would be more protective than folic acid alone (122). The PONTI (Prevention of Neural Tube defects by Inositol) study recruited women who wished to become pregnant after experiencing ≥1 previous NTD-affected pregnancy (119, 122). Supplementation of 14 pregnancies with myo-inositol (1 g) and folic acid (5 mg) daily, starting before conception and continuing until the end of 12th week of pregnancy, led to the birth of healthy unaffected infants in all cases. By comparison, 19 established pregnancies supplemented with a placebo and folic acid resulted in the birth of 18 normal infants and 1 fetus diagnosed with anencephaly. Importantly, no adverse effects of the myo-inositol supplementation in mothers or their infants were reported (122).

Although, collectively, these maternal myo-inositol supplementation studies (119–122) have yielded encouraging results, they are as yet of insufficient size to support the combined use of myo-inositol and folic acid supplements as a public health intervention to prevent NTDs. A larger number of women would need to be recruited to a fully powered study (4, 122). However, taken together, they do suggest that myo-inositol, as a simple and inexpensive nutrient supplement, could potentially be protective against NTD recurrence in folic acid-nonresponsive cases, making it an appealing candidate for testing in future clinical studies. Furthermore, they raise the possibility that myo-inositol could modulate the causative underly ing defect(s) that leads to the formation of an NTD, or enhance the process required for neural tube closure that is not responsive to folic acid supplementation alone. The loci of inositol’s action remain to be fully delineated, although impaired phosphoinositide and inositol polyphosphate signaling has been proposed as a potential pathway in NTD pathogenesis (4).

Conclusions
Myo-inositol, in addition to folic acid, is a nutritional supplement that may abrogate the pathogenesis of NTDs. Myo-inositol can be synthesized endogenously from glucose-6-phosphate and, together with inositol from the diet, may influence circulating concentrations. In the first trimester of pregnancy, the coelomic fluid that bathes the yolk sac, an organ of maternal–embryonic nutrient exchange, contains high concentrations of inositol and other polyols. These likely derive from maternal plasma that percolates from the maternal spiral arteries and/or from uterine decidual gland secretions, together with potential synthesis by the placenta and embryo/fetus. This indicates that the polyol metabolic pathway in the human conceptus is highly active in the early weeks of pregnancy to maintain ATP concentrations and cellular redox potential while the embryo develops in a low oxygen environment. We report preliminary evidence that the SLCA13 (HMIT), SLC5A3 (SMIT1), and SLC5A11 (SMIT2) genes are all expressed in both first-trimester placenta and human yolk sac matched from the same pregnancy. Together, these transporters may mediate myo-inositol uptake from coelomic fluid. Myo-inositol synthesis de novo from glucose-6-phosphate may also be possible as the ISYNA1 gene, which encodes myo-inositol-1-phosphate synthase, is expressed in the human placenta and yolk sac. These lines of evidence lead us to hypothesize a functional role for the human yolk sac in myo-inositol provision for the developing embryo, by uptake from coelomic fluid, as well as capacity for de novo myo-inositol synthesis.

Animal studies indicate that myo-inositol supplementation reduces the frequency of NTDs in a mouse strain that is nonresponsive to folic acid. Moreover, diabetic rats treated with myo-inositol had fewer NTD-affected fetuses. In clinical studies, myo-inositol supplements may have a similar effect in preventing NTDs unresponsive to folic acid, lending support to the importance of maternal myo-inositol for the developing embryo. This article highlights the possibility that the human yolk sac may be a contributor to embryonic myo-inositol provision, underscoring the potential for myo-inositol to participate in multiple inositol signaling pathways that regulate a diverse array of cellular mechanisms. Thus, further studies investigating the expression and functionality of human yolk sac myo-inositol transporters, as well as myo-inositol synthesis capacity, would lead to an improved appreciation of the role of the yolk sac in embryonic development, when neural tube closure and embryonic organogenesis are occurring. Further, a better understanding of maternal myo-inositol transport by the human yolk sac to the developing embryo would add to the mechanistic framework that supports myo-inositol’s use in clinical practice to prevent NTD recurrence in cases deemed folate nonresponsive.

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