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Neural tube defects – recent advances, unsolved questions and controversies

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Abstract

Neural tube defects (NTDs) are severe congenital malformations affecting around 1 in every 1000 pregnancies. Here we review recent advances and currently unsolved issues in the NTD field. An innovation in clinical management has come from the demonstration that closure of open spina bifida lesions *in utero* can diminish neurological dysfunction in children. Primary prevention by folic acid has been enhanced through introduction of mandatory food fortification in some countries, although not yet in UK. Genetic predisposition comprises the majority of NTD risk, and genes that regulate folate one-carbon metabolism and planar cell polarity have been strongly implicated. The sequence of human neural tube closure events remains controversial, but study of mouse NTD models shows that anencephaly, open spina bifida and craniorachischisis result from failure of primary neurulation, while skin-covered spinal dysraphism results from defective secondary neurulation. Other ‘NTD’ malformations, such as encephalocele, are likely to be post-neurulation disorders.

Introduction

Neural tube defects (NTDs) affect an average of 1 in every 1000 established pregnancies world wide ¹, although variations in NTD prevalence have been reported from 0.2-10 per 1000 in specific geographical locations. Higher frequencies occur in miscarriage material ². NTDs rank amongst the commonest of birth defects, alongside congenital heart anomalies and genito-urinary defects ³. NTDs have a long history: reports of fetuses and infants with anencephaly, myelomeningocele and craniorachischisis extend back to Ancient Egyptian times ⁴. Moreover, throughout the past 60 years, a striking progression of diverse bio-medical advances has impacted the NTD field, meaning that this topic has rarely been ‘out of the news’.

Record and McKeown’s landmark paper ⁵ in 1949 first raised awareness of the complex epidemiological features of NTDs. These include marked variations in NTD prevalence between geographical locations and ethnic groups, variation with socioeconomic status, pregnancy order in multiparous women and the striking female preponderance of

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anencephaly⁶. Carter's analysis in 1971 of the epidemiological data⁶ led to our persisting view of a multi-factorial NTD aetiology. Modern findings support a multi-gene predisposition, together with a role for 'environmental' factors such as the diabetic milieu or folate status.

In this Review we consider the clinical management and primary prevention of NTDs, advances in the understanding of NTD causation, and NTD pathogenesis. We note a number of unsolved questions and controversial topics.

Clinical features and management

Clinical severity of NTDs varies greatly (Table 1). Open lesions affecting the brain (anencephaly, craniorachischisis) are invariably lethal before or at birth. Encephalocele can also be lethal depending on the extent of brain damage during herniation. Open spina bifida is generally compatible with postnatal survival, although the resulting neurological impairment below the level of the lesion can lead to lack of sensation, inability to walk and incontinence. Associated conditions include hydrocephalus, which often requires cerebrospinal fluid shunting, vertebral deformities, and genitourinary and gastrointestinal disorders. Closed spinal lesions are generally less severe and can be asymptomatic, as with spina bifida occulta which is considered a variant of normal. However, lumbosacral spinal cord tethering may be present in spinal dysraphism, and can lead to lower limb motor and sensory deficits, and a neuropathic bladder.

Before the 1970s, management of open spina bifida consisted solely of palliative surgical and medical support. While children generally survived if their lesion was closed surgically, thereby avoiding ascending infection, neurological outcome varied markedly with the vertebral level of lesion (i.e. higher defects had greater neurological handicap). This led to suggestions that surgery should be offered only in cases with a better prognosis⁷. An ethical debate ensued, around whether surgical treatment should be withheld, but this was superseded in the 1970s when methods for prenatal diagnosis of open NTDs were developed. Initially, diagnosis was based on measurement of alpha-fetoprotein (AFP) concentration in the amniotic fluid and maternal blood^{8,9}, but later technological improvements enabled ultrasound to replace AFP measurement as the mainstay of prenatal diagnosis¹⁰. Today, most fetuses with NTDs are diagnosed prenatally in developed countries, and many are aborted therapeutically. In contrast, large numbers of babies with NTDs continue to be born in developing countries where prenatal diagnosis is not routine, as well as in countries where therapeutic abortion is either illegal, or not practised owing to religious or cultural views.

In human and mouse embryos, the persistently open spinal cord undergoes relatively normal neuronal differentiation during the embryonic period, including development of spinal motor and sensory function even below the lesion level¹¹. This demonstrates that neural tube closure is not required for subsequent events of neuronal differentiation. As gestation progresses, however, neurons die within the exposed spinal cord, revealing that the amniotic fluid environment is toxic for cells that would normally be contained within the closed neural tube. Axonal connections are interrupted, and function is lost^{11,12}. Hence,

neurological disability in open spina bifida is a 'two-hit' process: failed neural tube closure followed by neurodegeneration *in utero*. This has encouraged attempts to arrest or prevent further neurodegeneration by covering the persistently open neural tube as early as possible during fetal development.

Surgical repair *in utero* for early open spina bifida has been practised in several centres in the USA for the past 15 years¹³. An important recent development was the report of a controlled clinical trial to evaluate the success of this procedure. The Management of Myelomeningocele Study (MOMS)¹⁴ randomly assigned fetuses with prenatally diagnosed myelomeningocele to either *in utero* surgery or standard post-natal repair. The trial showed that fetal surgery brings significant short-term benefits for the newborn child, including a 50% reduction in shunting for hydrocephalus and a significant improvement in spinal neurological function. Against this was a significantly higher rate of premature birth and maternal complications such as uterine dehiscence at the operation site in the *in utero* group. While long-term outcomes for children following this surgical intervention remain unknown, these pioneering studies will no doubt encourage other centres to consider implementation of *in utero* surgery.

Primary prevention of NTDs

In the 1970s, Smithells and colleagues noted that several vitamins (folate, riboflavin and vitamin C) had reduced concentrations in the serum of mothers pregnant with NTD fetuses¹⁵. They performed an intervention trial of peri-conceptional Pregnavite Forte F, a multi-vitamin supplement containing 0.36 mg folic acid (FA), to assess its possible effect in preventing NTD recurrence in high-risk women with a previous affected pregnancy. The ethics committees denied requests for randomisation at this time, so the findings of significant prevention by Pregnavite Forte F¹⁶ were not universally accepted as definitive evidence of prevention¹⁷. In due course, a randomised, double blind study (the MRC trial) was performed which specifically assessed 4 mg FA separately from multi-vitamins and demonstrated that FA is the essential factor for significant prevention of NTD recurrence¹⁸. Subsequently, a randomised clinical trial in Hungary of a multivitamin supplement containing 0.8 mg FA was shown to significantly prevent the first occurrence of NTDs¹⁹, an important finding considering that 95% of all NTD cases are first occurrences in a family. A further clinical trial, based in China, demonstrated a fall in NTD prevalence subsequent to introduction of FA supplementation²⁰.

The MRC trial led to the recommendation that all women planning a pregnancy should consume 0.4 mg FA per day (the dose used in the Smithells trials), and that women at high risk of NTD should receive 4-5 mg per day. However, despite widespread public health education efforts in the UK and other countries, the prevalence of NTDs did not decrease during the decade following the MRC trial publication²¹. In the USA, a campaign of governmental lobbying²² eventually achieved its aims and mandatory fortification of bread flour with FA was introduced in 1998. Fortification was introduced soon after in Canada, and then throughout South America, South Africa, Australia, and other countries. Although NTD rates were falling in several countries prior to this period²³, most authorities agree that the decision to fortify with FA, ensuring a more favourable folate status in women who

become pregnant, has contributed significantly to reducing the number of pregnancies affected by NTDs²⁴. It is notable that no European countries, including the UK, have yet to implement food fortification. Other strategies for improving supplementation include incorporation of folate within an oral contraceptive²⁵, and the use of supplements that contain a more ‘bioavailable’ form of folate. Compounds such as 5-methyltetrahydrofolate (6S-5-MTHF) may offer a means of enhancing folate status more effectively than FA in some individuals²⁶. However, an appropriate format to retain stability in food is required²⁷, and a formal trial for prevention of NTDs has not yet been performed.

Surveys of NTD prevalence show that the decline following food fortification²⁴ has been smaller than expected from the MRC trial. While some have advocated increasing doses of FA, in order to prevent a larger proportion of total NTDs²⁸, most authorities accept that a proportion of cases, perhaps 0.7-0.8 per 1,000 pregnancies, are likely to persist regardless of FA usage, and that little additional benefit will accrue from a further increase in dose level^{29,30}. In other words, a proportion of NTDs are likely to be ‘FA-resistant’, and perhaps of different aetiology from the FA-sensitive subgroup. This concept is well established in mouse models of NTDs where some genetic types are FA-preventable while others are FA-resistant³¹. One potential adjunct therapy that has arisen from the mouse studies is the use of inositol, which is effective in preventing a large proportion of spinal NTDs in the *Grhl3* (*curly tail* mutant) mouse, where FA is ineffective³². Uniquely among vitamins, inositol deficiency leads to NTDs in rodent embryos³³. A randomised clinical trial to evaluate inositol for prevention of human NTD recurrence is currently underway in the UK.

Controversies and unsolved questions in NTD prevention

Are NTDs a vitamin-deficiency disorder?

The finding that FA can prevent many NTD cases is often interpreted as showing NTDs to be a ‘vitamin-deficiency’ condition³⁴. Indeed, both folate and vitamin B12 deficiency are statistical risk factors for NTDs³⁵. However, maternal folate levels in most affected pregnancies are within the ‘normal’ range^{35,36}, arguing against a simple folate-deficiency model. In mice, severely FA-deficient wild-type mothers do not have embryos affected by NTDs, although intrauterine growth retardation is routinely observed^{37,38}. The frequency of cranial NTDs is exacerbated by maternal folate deficiency in mutant *plotch* (*Pax3*) embryos, whereas wild-type littermates are never affected by NTDs³⁹. Similarly, in the *Shmt* knockout mouse, the development of NTDs is seen solely in mothers that are folate deficient⁴⁰. Clearly, folate deficiency is a risk factor for NTDs, but only in the presence of a predisposing genotype.

Could FA ‘prevent’ NTDs by killing affected embryos?

This concept, termed ‘terathanasia’ is theoretically possible, as the disappearance of a proportion of NTD cases, owing to early pregnancy loss, might be interpreted as primary prevention⁴¹. There was a small excess of miscarriages in the multivitamin-treated group of the Hungarian randomised trial¹⁹, but this has been interpreted as FA encouraging survival of some pregnancies to a stage when their loss can be recognised (as miscarriage). In several mouse NTD models, embryos whose genotype destined them to develop NTDs can be

normalised by FA^{42,43}. Moreover, in the *splotch* (*Pax3*) model, folate-deficiency exacerbates cranial NTDs, consistent with true primary prevention by FA³⁹. However, exposure of several mouse NTD strains to dietary FA supplementation has produced a more diverse range of responses, with apparent exacerbation of NTDs in some cases⁴⁴. This variation in response may result in part from the widely varying FA dose levels used in different mouse strains, often amounting to a 100-fold excess compared with human supplementation⁴⁵. Interestingly, however, serum folate concentrations are generally similar in supplemented mice and humans⁴⁴. A further consideration is that various pathogenic mechanisms are known to underlie NTDs, in mice and probably also in humans; hence, the interaction of FA supplementation with these mechanisms is also likely to be heterogeneous.

How does FA promote normal neural tube closure?

This fundamental question has received little attention compared with the hundreds of publications on clinical and epidemiological aspects of FA supplementation. So far, we know that FA has a direct effect on the neurulation stage embryo, as treatment of genetically predisposed mouse embryos *in vitro* can normalise neural tube closure⁴². FA enters one-carbon metabolism, which has two main outputs: production of pyrimidines and purines for DNA replication during cell proliferation, and donation of methyl groups to macromolecules including DNA, proteins and lipids (Figure 1). Cell multiplication plays a key role in neural tube closure^{46,47}, encouraging the hypothesis that enhanced cell proliferation may be a key effect of FA. On the other hand, methylation of genomic DNA and histones is increasingly being implicated in the (epigenetic) regulation of gene expression⁴⁸, and could underlie the action of FA in preventing NTDs. Detailed analysis of FA prevention of NTDs in animal models may resolve this issue in the coming years.

Causes of NTDs

Both genetic and non-genetic factors are involved in the aetiology of NTDs, with up to 70% of the variance in NTD prevalence due to genetic factors⁴⁹. Evidence for genetic causation includes an increased recurrence risk for siblings of index cases (2-5%) compared with the 0.1% risk in the general population, together with a gradually decreasing frequency in more distant relatives. Women with two or more affected pregnancies have a higher risk (~ 10%) of further recurrence⁵⁰. NTD prevalence is greater in like-sex twins (assumed to include all monozygotic cases) compared with unlike-sex pairs, consistent with a significant genetic component. Nevertheless, NTDs rarely present as multiple cases in families; instead a sporadic pattern is usually observed. Taken together with the relatively high prevalence of NTDs across the world, this is consistent with a multifactorial polygenic or oligogenic pattern of inheritance, and an important role for non-genetic factors.

The genomics revolution of the last 15 years has impacted NTD research in two major ways: first, in providing the tools necessary to evaluate candidate genes for NTD causation and, second, in providing a wealth of mouse genetic NTD models (see Pathogenesis, below) which have stimulated many studies of human disease aetiology. In the near future, a full genome-wide assessment of interacting variants, including coding, regulatory and epigenetic marks, will be possible to determine an individual's risk of developing a NTD. Indeed it may well be necessary to adopt such a strategy, if we are to unravel the complex

multifactorial causation of these conditions. However, in view of the likely causal heterogeneity amongst sporadic NTDs, the implementation of this approach is highly demanding, requiring large numbers of samples for analysis. To date, genes in two main areas of biology have yielded positive findings with regard to NTD aetiology: folate one-carbon metabolism and non-canonical Wnt signalling (the planar cell polarity pathway).

Folate-related genes

Given the historical relationship between FA and NTDs, it is not surprising that folate pathway genes have been most intensively studied (Figure 1). Positive associations have been reported between specific folate-related gene variants and NTDs in a number of case-control studies⁵¹⁻⁵³. For example, methylenetetrahydrofolate reductase (*MTHFR*) encodes a key cytoplasmic enzyme of folate metabolism, that generates 5-methyl tetrahydrofolate for homocysteine remethylation. The *MTHFR* polymorphism C677T (rs1801133) is associated with a roughly 1.8-fold increased risk of NTDs, although the predisposition is detectable only in non-Hispanic populations⁵⁴. A further significant risk factor is the R653Q variant (rs2236225) of *MTHFD1*, a trifunctional enzyme that catalyses the conversion of tetrahydrofolate to 5,10 methylenetetrahydrofolate^{53,55}.

Most recently, genes that encode enzymes functioning in mitochondrial one-carbon metabolism have also been implicated in NTD aetiology. An intronic polymorphism in *MTHFD1L*, the gene for mitochondrial 10-formyl-THF synthetase, is associated with increased risk of NTD⁵⁶, while two genes encoding enzymes of the glycine cleavage system, *AMT* and *GLDC*, have been found to harbour a number of missense (i.e. amino acid-changing) genomic alterations in NTD cases, but not in unaffected controls⁵⁷. In the case of *GLDC*, these variants diminish enzyme activity indicating a functional effect on folate metabolism. Each of these enzymes markedly affects flux of formate from the mitochondrion into the cytoplasm, which accounts for approximately 75% of one-carbon units entering folate metabolism⁵⁸.

Hence, genetic variants that reduce the 'efficiency' of folate one-carbon metabolism increase the risk of NTDs. These findings are consistent with a study of cell lines derived from NTD fetuses, in which a subset were found to exhibit apparent inborn errors of folate metabolism, as indicated by diminished thymidylate biosynthesis⁵⁹. Strikingly, however, under folate-replete dietary conditions, only the mitochondrial enzymes *Mthfd1l* and *Amt* have been found to cause NTDs in knockout or gene trap mice^{57,60}. Disruption of the cytoplasmic enzymes *Mthfr* and *Mthfd1* do not cause mouse NTDs^{61,62}, while exencephaly occurs in *Shmt* null embryos under folate-deficient conditions⁴⁰. This may indicate that the mitochondrial contribution to folate metabolism is particularly relevant and/or sensitive in terms of mammalian neural tube closure.

Planar cell polarity genes

At the onset of neurulation, the embryo undergoes lengthening and narrowing of the initially disc-shaped neural plate in order to ensure that the neural folds are spaced sufficiently close together for closure to begin^{63,64}. This elongation of the neural plate and underlying mesoderm requires a lateral to medial displacement and intercalation of cells, termed

convergent extension⁶⁵. At the molecular level, convergent extension cell movements are dependent on non-canonical Wnt signalling: the planar cell polarity (PCP) pathway (Figure 2), which signals via frizzled membrane receptors and cytoplasmic dishevelled, but does not involve downstream stabilisation of beta-catenin⁶⁶.

Indications of a possible involvement of the PCP pathway in human NTDs came from the discovery of PCP gene involvement underlying severe NTDs in several mouse mutants. Mutations in the trans-membrane proteins *Vangl2*, *Celsr1*, *Ptk7* and *Fzd3/6* (double mutant), and the cytoplasmic proteins *Dvl1/2/3* and *Scrb*, all result in craniorachischisis, a severe NTD (Table 1) in which closure fails along most of the body axis, yielding an open neural tube from midbrain to low spine⁶⁷. An increasing number of studies have subsequently reported unique and predominantly missense variants in PCP genes of NTD patients as likely causal alleles (Table 2). However, the finding of non-synonymous amino acid changes in affected humans but not in controls, whilst suggestive, does not prove their causal role in the NTDs. Functional evidence is needed to demonstrate whether the specific human ‘mutations’ actually cause protein dysfunction or, better still, reproduce the NTD phenotype in an animal model.

To date, assays of PCP protein function including interaction with Dishevelled^{68,69} and translocation to the plasma membrane⁷⁰ have identified functional defects in NTD-associated variants of *VANGL1*, *VANGL2*, *CELSR1* and *SCRIB*. Several *VANGL1* missense variants block the rescuing effect of *Vangl1* mRNA on the *Vangl2* (trilobite) mutant phenotype in zebrafish⁷¹. It remains to be determined whether any of the putative NTD-causing variants in human PCP genes would also reproduce an NTD phenotype in an experimental mammal, such as a knock-in mouse strain.

Genetic causes of encephalocele

In contrast to open NTDs, occipital encephalocele is often syndromic, most commonly as part of Meckel syndrome. A number of genes have been identified in the causation of this condition: *MKS1*, *MKS2* (*TMEM216*), *MKS3* (*TMEM67*), *RPGRIPL1*, *CEP290* [3]. MKS proteins play a key role in the structure and function of primary cilia, protrusions of the cell surface that are rooted in the centrosome and undergo a disassembly and reassembly cycle as the cell proliferates. Primary cilia are essential for signalling pathways, for example downstream of hedgehog proteins. Many, often individually rare, disorders are now known to be causally associated with genes required for ciliary structure and function, which has led to the concept of ‘ciliopathies’. How encephalocele results from disordered ciliary function is currently unknown.

Environmental factors

Few non-genetic factors have been definitively associated with human NTDs. This contrasts with the wide variety of teratogenic agents known to cause the defects in rodents⁷². Of particular clinical significance is valproic acid (VPA), an anticonvulsant that increases risk of spinal NTDs by approximately 10-fold when taken during early in pregnancy⁷³. Although the teratogenic mechanisms underlying anticonvulsant action may involve anti-folate effects, particularly for carbamazepine⁷⁴, recent findings with VPA suggest a potent

histone deacetylase (HDAC) inhibitory activity. This could disturb the balance of protein acetylation versus deacetylation, similar to the action of the HDAC inhibitor, trichostatin-A, which causes NTDs in mice⁷⁵. A further interesting environmental teratogen with proven effect in humans is the fungal product fumonisin, which was responsible for a 2-fold increase in NTD prevalence along the Texas-Mexico border in the early 1990s⁷⁶. Fumonisin is a potent NTD-causing teratogen in mice, with marked effects on spingolipid metabolism, that likely disturbs downstream embryonic gene expression⁷⁷. Other 'environmental' factors implicated in the aetiology of NTDs include maternal diabetes⁷⁸, maternal obesity⁷⁹, and exposure to high temperatures during early pregnancy⁸⁰.

While environmental causes of birth defects are perhaps the most preventable of predisposing factors, it is important to note that only a very small proportion of all congenital disorders have a known environmental cause: estimated at 0.12 cases per 1000 births (0.5% of all defects) in a recent survey of European pregnancies³. Moreover, genetic variation is likely to play an important role in determining the susceptibility of a particular pregnancy to non-genetic factors. For example, marked differences are routinely observed between different inbred mouse strains for many teratogenic factors including VPA and fumonisin^{77,81}. In humans, single nucleotide polymorphisms in genes associated with types I and II diabetes mellitus have been associated with NTDs^{82,83}.

Controversies and unsolved questions

Can FA supplementation be targeted to genetically-defined 'sensitive' pregnancies?

Inheritance of a 'predisposing' folate enzyme variant, perhaps affecting *MTHFR* or *MTHFD1*, might be predicted to affect an individual's response to exogenous FA supplementation. Carriers could require a larger dose of FA than wild-type individuals, to be 'protected' from NTDs. Hence, genotyping for known (or novel) risk variants might provide a means of FA targeting. A multivariate analysis of NTD cases (or mother-fetus pairs) is required to examine this possibility, with assessment of all known folate-related genetic variants, indices of folate supplementation and serum/red cell folate, homocysteine and other metabolites.

Do human and mouse phenotypes correspond in cases of shared genetic aetiology?

Despite the finding of PCP gene mutations in both mice and human NTDs, the phenotypes of humans and mice do not always correspond closely. For example, the human NTDs associated with heterozygosity for *VANGL2* variants have included anencephaly, holoprosencephaly (not a defect of neural tube closure) and closed spina bifida^{69,84}. By contrast, mouse *Vangl2* mutants exhibit craniorachischisis in homozygotes and low open spina bifida in compound heterozygotes with other gene mutations⁵². Even more puzzling, human 'mutations' have been found in *VANGL1* and *PK1*^{68,85} despite there being no NTD phenotype in homozygous mouse mutants for these genes (Table 2). Only two PCP genes, *CELSR1* and *SCRIB*, have been associated with the same NTD phenotype, craniorachischisis, in both mice and humans⁷⁰, whereas *VANGL2* mutations were not identified in humans with craniorachischisis⁸⁶. Based on a polygenic model of NTD causation, we would predict that current genetic findings are incomplete, with additional

'interacting' genetic variants remaining to be discovered. The precise combination of predisposing variants may determine whether an individual develops anencephaly, spina bifida or craniorachischisis.

NTD pathogenesis

NTDs comprise a diverse set of birth defects that are usually considered to arise during the third and fourth weeks post-fertilisation. However, there remain many questions about the precise timing of origin of specific anomalies that are included under the umbrella of 'NTDs'. Moreover, we have a limited understanding of the cellular and molecular mechanisms by which human NTDs arise during embryonic development. In fact, there has been a strong tendency for investigators of the clinical, epidemiological and FA-prevention aspects of NTDs to consider embryonic development as a 'black box' that can be left firmly closed. On the other hand, as genetic risk factors start to emerge from modern genomics research, it is vital to be able to understand when and how such gene variants might exert their effects. Similarly, in attempting to optimise FA-mediated prevention, and introduce new preventive therapies, it is important to appreciate the precise embryonic mechanisms that might be the targets of therapeutic interventions.

Advances in developmental studies of mouse neurulation

The availability of more than 250 different models of open NTDs in mice⁸⁷ is enabling increasingly sophisticated analysis of the neurulation events, at tissue, cellular and molecular levels. Because this large range of mouse models covers the majority of NTD types seen in humans, it has also been possible to build a picture of the events that are specific to each stage of neural tube formation, and therefore to the NTDs that arise from defects at particular stages. One potential limitation to mammalian research is the relative inaccessibility of the developing embryo within the uterus. However, access to neurulation stages is greatly facilitated by use of whole mouse embryo culture, in which intact mid-gestation embryos encased within their extraembryonic membranes, can be grown *in vitro* during the entire period of neurulation⁸⁸. Moreover, as live imaging techniques based on confocal microscopy become increasingly sophisticated and adaptable, a new era is beginning of real-time information on the dynamic events of neurulation in mammals through the imaging of cultured mouse embryos⁸⁹. Non-mammalian models, especially chick, frog and zebrafish, continue to provide insight into some of the key pathways and cellular mechanisms of neural tube formation⁹⁰⁻⁹².

Events of mouse neural tube formation

Neural tube formation is divided into primary (closure) and secondary (canalisation) phases. Primary closure is initiated at several discrete points along the rostro-caudal axis (Figure 3A): first, at the boundary between future hindbrain and cervical spine (termed Closure 1), then around 12 hours later at the boundary between future forebrain and midbrain (Closure 2) and soon afterward at the rostral extremity of the future forebrain (Closure 3)^{31,93}. The open regions of neural folds between the sites of initial closure are termed 'neuropores', and these close progressively as the neural tube 'zips up' bi-directionally from the sites of Closures 1 and 2, and in a caudal direction from the site of Closure 3. The anterior and

hindbrain neuropores complete closure within a few hours of Closures 2 and 3, whereas spinal neurulation continues zipping caudally along the growing spinal region until the posterior neuropore finally closes during embryonic day 10. This marks the end of primary neurulation, a process that has taken approximately 48 hours to be completed in mice.

Secondary neurulation follows on seamlessly from primary neurulation, and is the process by which the neural tube forms in the lower sacral and coccygeal regions^{94,95}. The caudal end of the embryo comprises the tail bud, which contains self-renewing stem cells whose derivatives condense into longitudinal cell masses. The most dorsal of these undergoes 'canalisation', converting the solid neural precursor into a hollow secondary neural tube. The stem cell population within the tail bud appears multipotent⁹⁶, giving rise to all non-epidermal tissues of the post-lumbar body, including neural tube and vertebrae. Probably for this reason, malformations and tumours (e.g. teratomas) of the sacral and coccygeal regions often embrace several tissue types.

Origin of NTDs during neural tube formation

Analysis of the mouse mutant *loop-tail* (*Vangl2* gene) has shown that craniorachischisis, the most severe NTD, results from failure of Closure 1⁹⁷. Most commonly, however, embryos complete Closure 1 but fail in later neurulation, presenting NTDs as separate open lesions of the cranial neural tube (exencephaly, progressing to anencephaly) and/or spinal neural tube (open spina bifida). The wave of 'zippering' closure down the body axis can arrest at any stage, yielding an open spina bifida of varying length. Hence, *Zic2* mutant mice fail early in spinal neurulation, owing to lack of dorsolateral neural plate bending⁹⁸. These mice exhibit a large spina bifida from thoracic level downwards. In contrast, spinal closure in the *curly tail* (*Grhl3*) mutant fails later, due to enhanced axial curvature of the body axis⁹⁹. This produces a spina bifida confined to the lumbo-sacral region. When secondary neurulation is disturbed, closed defects occur at sacro-coccygeal levels ('spinal dysraphism') in which the spinal cord is characteristically 'tethered' to adjacent tissues, reflecting faulty tissue separation during tailbud development.

Controversies and unsolved questions on neurulation

Do similar neurulation events occur in humans and mice?

The human neural tube begins to close at 17-18 days post-fertilisation and is discontinuous as in the mouse (Figure 3D). The site of closure initiation occurs at the same level as Closure 1 in mice, and the onset of closure from the extreme rostral end of the neural plate appears comparable to mouse Closure 3¹⁰⁰. Whether a Closure 2-like event exists in human embryos is controversial, but it seems increasingly likely that there is no independent closure initiation event in the midbrain or forebrain¹⁰⁰⁻¹⁰². Unlike mice, therefore, human brain formation is achieved by neurulation progressing directly between Closures 1 and 3, with completion of a single cranial (rostral) neuropore (Figure 3D). Interestingly, Closure 2 is also absent in the SELH/Bc mouse strain¹⁰³ and yet more than 80% of embryos successfully complete brain formation, demonstrating that Closure 2 is not obligatory, even in mice.

Do all NTDs result from defective neural tube closure?

A variety of malformations are included under the overall description of NTDs (Table 1) but do they all arise directly from abnormalities of primary or secondary neurulation? Historically, neurulation was depicted in text books as starting half-way along the embryonic body and progressing by ‘zippering’ towards the cranial and caudal ends, with closure of anterior and posterior neuropores respectively (Figure 3B). A major change in this view occurred when the idea of ‘multi-site closure’ was introduced, based on observations of neurulation stage mouse embryos¹⁰⁴. The origin of human NTDs¹⁰⁵ was re-interpreted, based on appearance of late fetuses and the ‘closure events’ that were thought to have been defective (Figure 3C). However, extrapolation from a late stage fetus to its embryonic origins is largely guesswork and subsequent studies showed that Closures 4 and 5 exist in neither mouse nor human neurulation^{31,100}. We have seen that Closure 2 likely does not exist in humans either. What remains is a relatively ‘simple’ pattern of human neurulation (Figure 3D), most akin to the original model (Figure 3B). While it is possible to explain craniorachischisis, anencephaly, open spina bifida and closed secondary neurulation lesions based on key embryonic events (Figure 4), other ‘NTDs’ including encephalocele, meningocele and iniencephaly are unlikely to arise directly from failure of neural tube formation, but more likely as post-neurulation disorders. This is consistent with the finding of a distinct aetiology for encephalocele as part of Meckel syndrome.

Conclusions

NTDs continue to provide a multifaceted challenge to epidemiologists, clinicians, and developmental biologists alike. Although their imminent eradication was predicted when prenatal diagnosis was introduced, and again after the discovery of the preventive effects of folic acid, in fact NTDs remain one of the commonest categories of birth defects worldwide. Their clinical severity and uncertain cause make them priorities for further research, whether to better target primary preventive measures, to improve in-utero surgery for prenatal repair, or to identify the causative genes to provide an objective basis for individual genetic counselling. In this Review, we provide evidence that NTDs are not vitamin-deficiency disorders in the way that rickets results from early vitamin D deficiency. Rather, folate one-carbon metabolism is a key mechanism in the development of NTDs that is affected by, and interacts with, both genetic and environmental factors. The application of new genomic technologies to NTDs should herald the identification of many further risk factors, enabling understanding of the entire range of causative factors that affect the mother and her neurulation stage embryo. Being accurate about exactly how the neural tube is formed during embryogenesis is important, and we have shown how extrapolation backwards from late fetal appearance to presumed early embryonic events is hazardous and, in the case of NTDs, has led to misconceptions about the developmental origin of these disorders.

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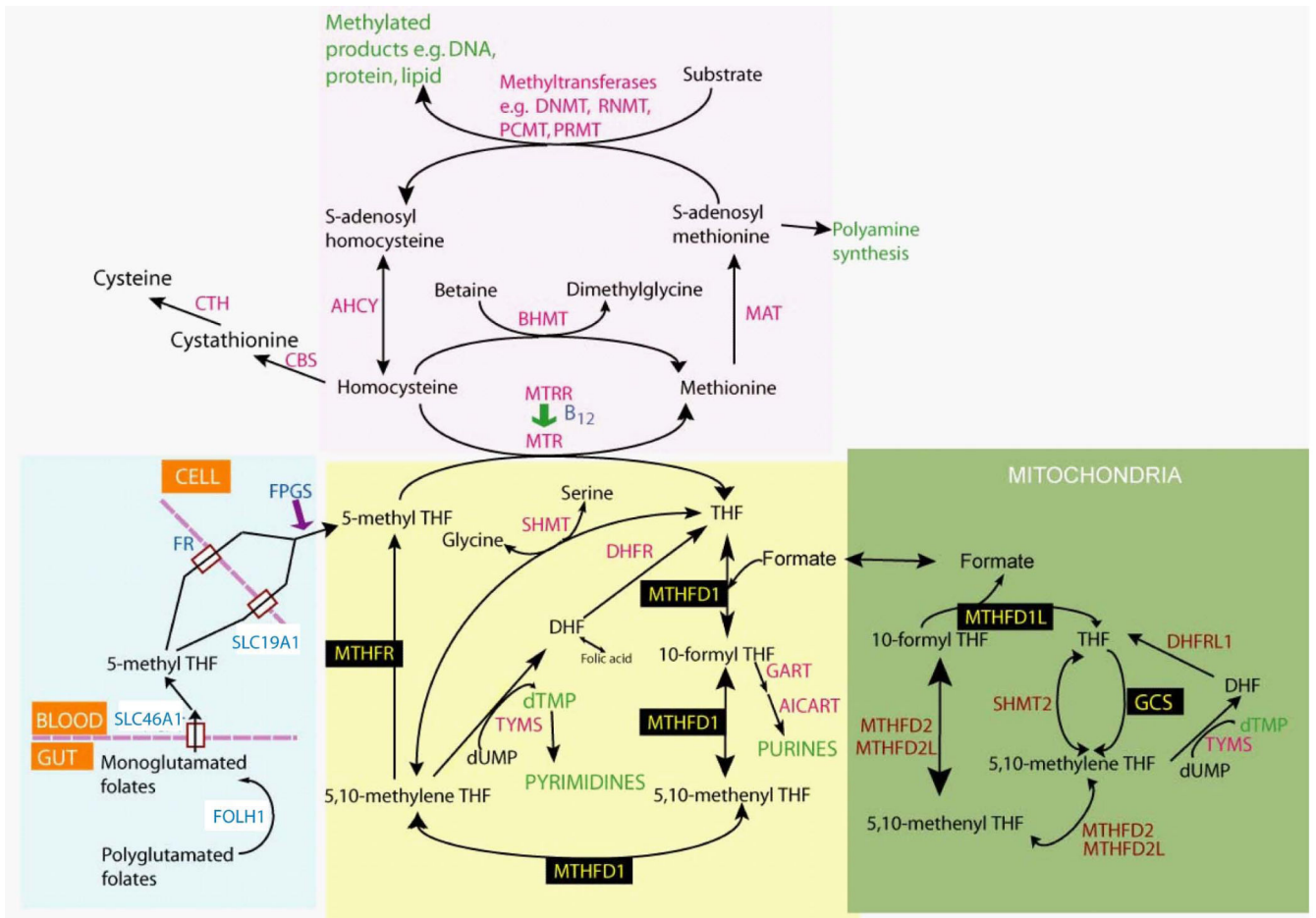


Figure 1. Summary of folate one-carbon metabolism showing the main pathways and reactions. Blue shading: processing of folates in the digestive tract, transport and cellular retention (by addition of glutamates). Yellow shading: transfer of one-carbon groups between folate molecules for purine and pyrimidine biosynthesis. Pink shading: reactions of the methylation cycle that generate SAM, the universal methyl group donor. Green: mitochondrial reactions that generate formate via cleavage of glycine. Enzymes whose genetic variation have been implicated in human NTDs are indicated in black boxes. Figure modified from Greene et al, 2009⁵².

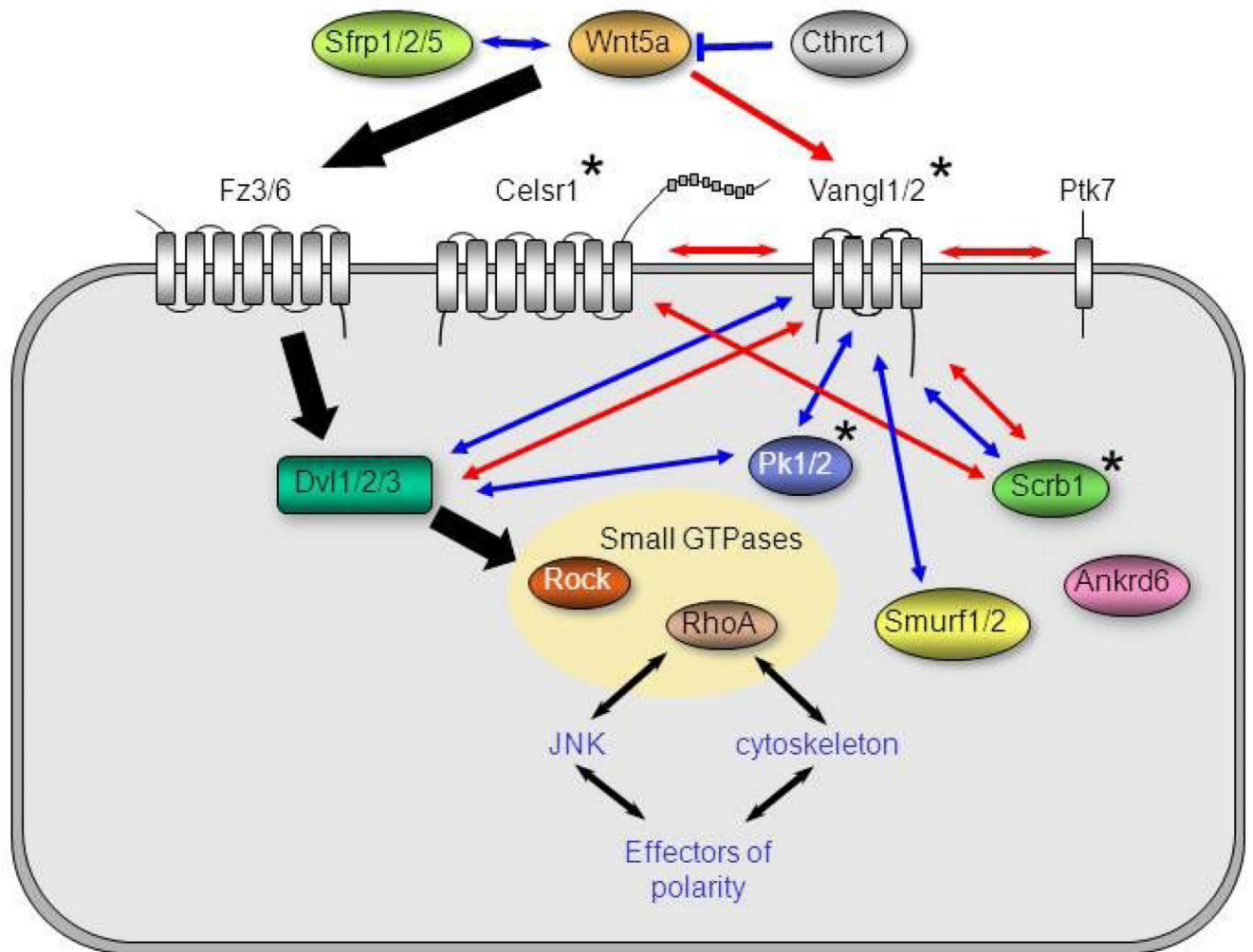


Figure 2. Summary of non-canonical Wnt signalling in a mammalian cell.

Black arrows indicate the signalling pathway necessary for establishment of planar cell polarity (PCP). Known biochemical interactions are indicated by blue arrows and genetic interactions are shown by red arrows. Genes that have been implicated in human NTDs are indicated by asterisks. Figure modified from Greene et al, 2009⁵².

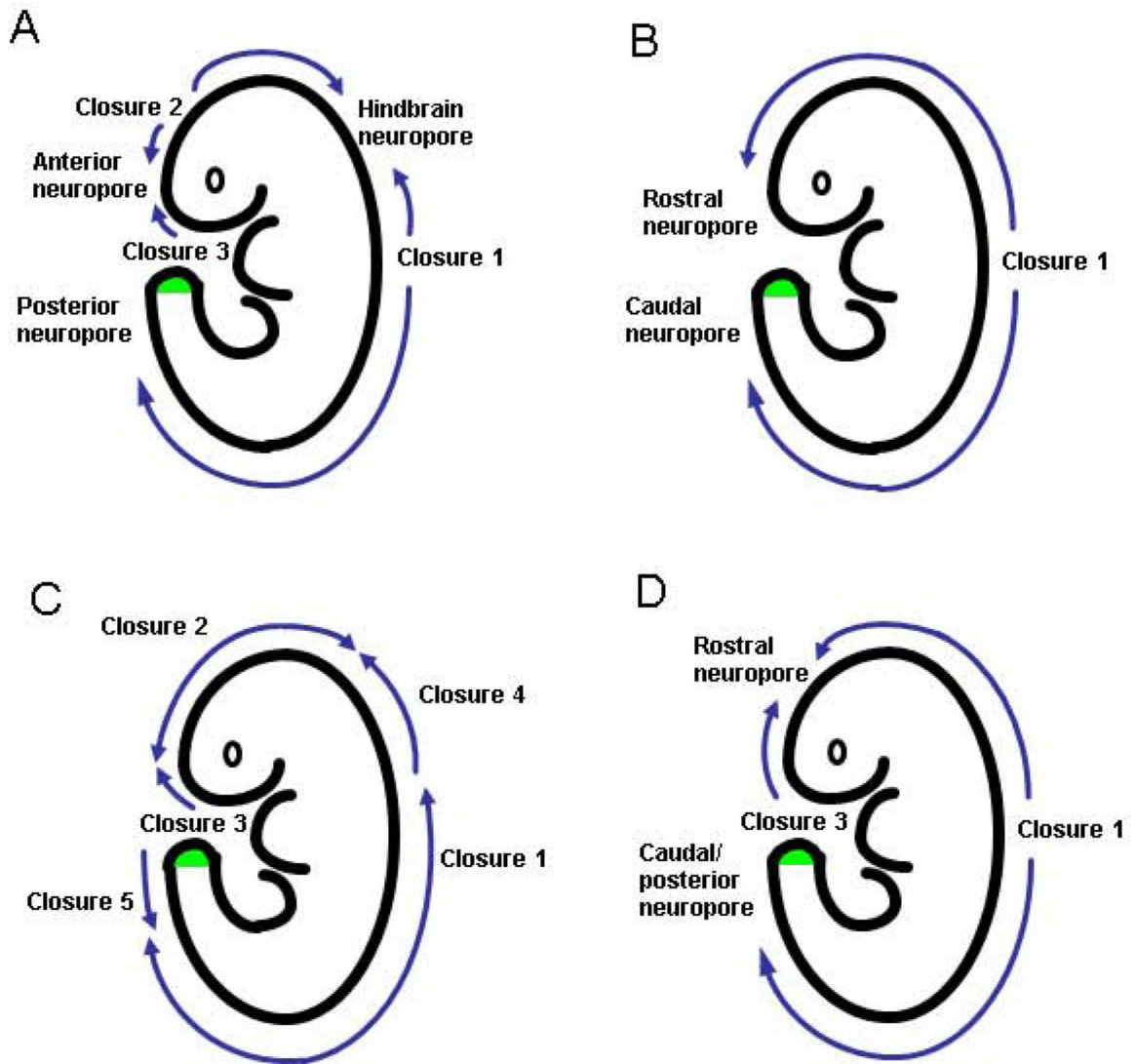


Figure 3. Schematic showing different concepts of how mouse (A) and human (B-D) embryos undergo primary neurulation.

The site of secondary neurulation in the tailbud is indicated by green shading. (A) Pattern of mouse neural tube closure, as experimentally verified in multiple mouse strains³¹. (B) The original concept of human closure in which bidirectional zippering occurs from an initiation site (Closure 1) towards the rostral and caudal extremities. (C) Modified concept based on mouse multi-site closure, as used for retrospective interpretation of human NTDs¹⁰⁵. (D) Pattern of human neural tube closure based on embryo observation¹⁰⁰.

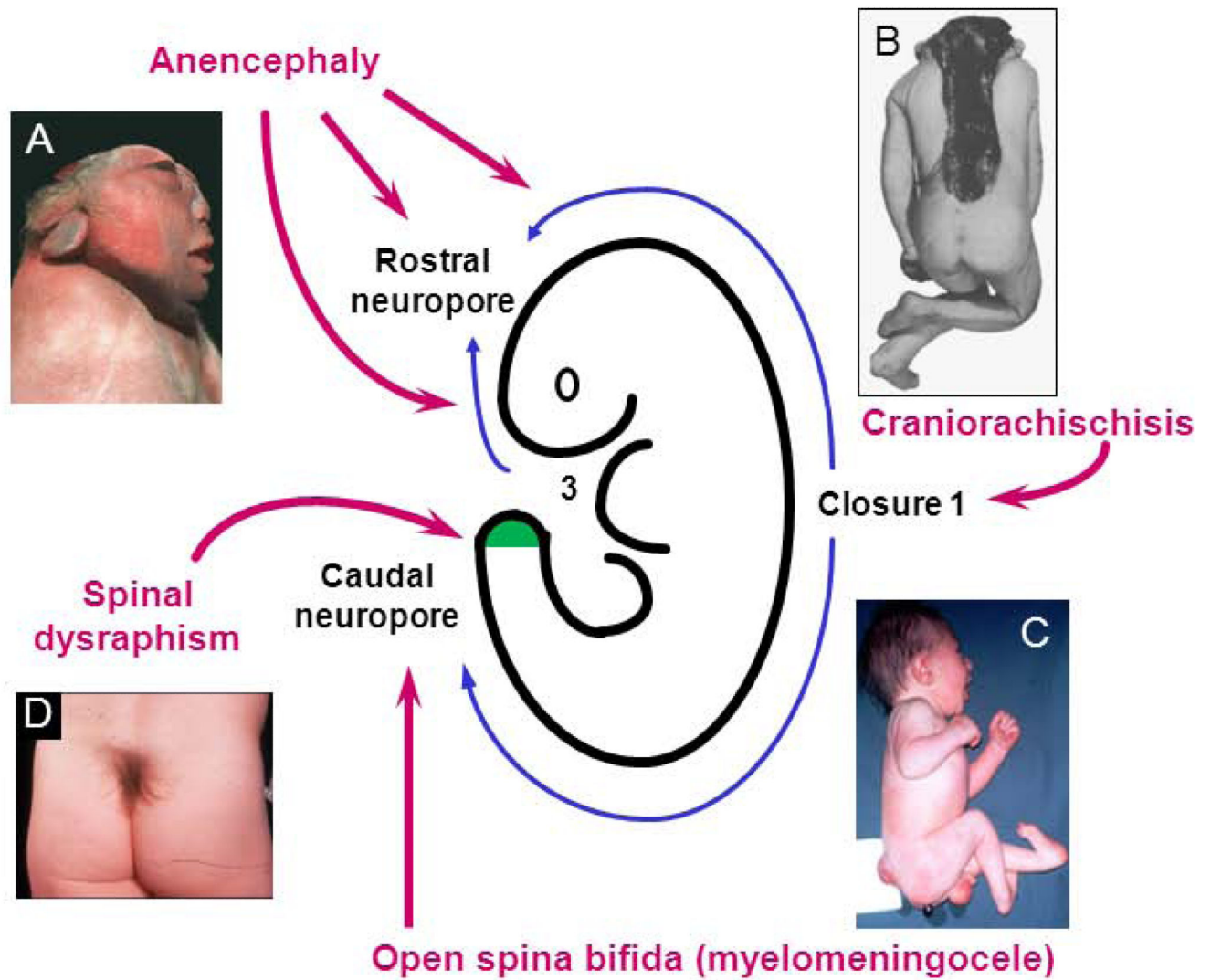


Figure 4. Sites of origin of NTDs in the human embryo directly resulting from disturbance of primary or secondary neurulation

(A) Anencephaly is the consequence of faulty cranial closure events; (B) Craniorachischisis arises when Closure 1 fails; (C) Open spina bifida results from failure of caudal neuropore closure; (D) Skin-covered spinal 'dysraphism' arises through disturbance of the secondary neurulation process. Figure modified from: Copp, 2005. In: R. A. Meyers (Ed.), *Encyclopedia of Molecular Cell Biology and Molecular Medicine*, 9, 119-138. Wiley-VCH, Weinheim (B,C); Copp, 2008. In: eLS. John Wiley & Sons Ltd, A20913, Chichester. <http://www.els.net> (D).

Table 1

Characteristics of the main types of NTDs

	Anencephaly	Myelomeningocele (open spina bifida; SB)	Craniorachischisis	Spinal dysraphism	Encephalocele
Relative frequency *	40%	50%	3%	Unknown	7%
Epidemiological features	Typical of NTDs as a whole; mostly sporadic	Typical of NTDs as a whole; mostly sporadic	Unknown; high prevalence noted in North China ¹⁰⁶	Unknown	Usually sporadic, but can be syndromic (e.g. in Meckel syndrome)
Sex ratio (F:M)	Marked female excess (3:1)	Variable in different populations; approximately equal overall	Female excess, as for anencephaly	Equal	Female excess among occipital lesions
Clinical presentation	Lack of brain and cranial vault; fetal loss or stillbirth	Open spinal cord covered by meningeal sac (SB cystica) or exposed (SB aperta); most commonly thoraco-lumbar, lumbar or lumbo-sacral; usually live birth; frequently associated with hydrocephalus post-natally	Anencephaly continuous with complete open spina bifida; fetal loss or stillbirth	Skin covered lesion involving 2 or more vertebrae, apparent only on radiography; hair tuft, lipoma or other cutaneous feature often co-exists	Meningeal sac, often containing brain tissue, protrudes from skull; commonly in occipital, parietal or fronto-ethmoidal locations
Prenatal diagnosis	Ultrasound from first trimester; elevated serum AFP	Ultrasound from first trimester; elevated serum AFP	Ultrasound from first trimester; elevated serum AFP	No	Ultrasound, depending on size of lesion
Surgical treatment	None; lethal beyond birth	Surgical closure post-natally or <i>in utero</i> in some centres; insertion of cerebro-spinal fluid shunt for hydrocephalus	None; lethal beyond birth	Untethering of spinal cord, usually in childhood	Repair by removal of sac and closure
Non-surgical treatment	None	Long-term treatment of hydrocephalus, skeletal, renal, gut and other secondary disorders	None	Treatment of genito-urinary disorders as common sequelae	Treatment of epilepsy and learning disorders as common sequelae
Genetic causation	Genes as for NTDs as a whole (see text)	Genes as for NTDs as a whole (see text)	Planar cell polarity genes are only positive findings	Unknown	<i>MKSI-3</i> , <i>RPGRIPL</i> , <i>CEP290</i> genes all identified as causal for Meckel syndrome (occipital encephalocele)
Non-genetic causation	Increased risk in diabetic pregnancy; no specific associations	Valproic acid exposure increases risk 10X; increased risk in diabetic pregnancy	None known	None known	None known
Primary prevention	FA, as for NTDs as a whole	FA, as for NTDs as a whole; inositol prevention of open spina bifida in <i>Grl3</i> mouse model	FA may prevent: North China frequency declined after FA introduced	FA-resistant? Lipomyelomeningocele frequency shows no decline after food fortification with FA ¹⁰⁷	FA may prevent: some evidence of decline after food fortification with FA
Embryonic origin	Failure of cranial neural tube closure	Failure of caudal neuropore closure	Failure of Closure 1	Defective secondary neurulation	Post-neurulation disorder?
Pathogenesis	Originates after failed closure as exencephaly;	Degeneration of exposed neural tissue following failed closure;	Combined anencephaly and myelomeningocele	Unknown	Herniation of meninges with or without brain tissue through defect in skull

Anencephaly	Myelomeningocele (open spina bifida; SB)	Craniorachischisis	Spinal dysraphism	Encephalocele
converted to anencephaly by degeneration of neural tissue and absence of cranial vault formation converted to anencephaly by degeneration of neural tissue and absence of cranial vault formation converted to anencephaly by degeneration of neural tissue and absence of cranial vault formation converted to anencephaly by degeneration of neural tissue and absence of cranial vault formation converted to anencephaly by degeneration of neural tissue and absence of cranial vault formation	absent absent absent absent absent	absent absent absent absent absent	absent absent absent absent absent	absent absent absent absent absent

* Relative frequencies relate to NTDs in established pregnancies, based on data in 108 and 109. Spinal dysraphism is not usually included within epidemiological studies of NTDs and, since its prevalence is poorly documented, a relative frequency is not given

Table 2
PCP genes and their mutant phenotypes in mice and humans

PCP genes	Phenotype in mouse mutant homozygotes	Phenotype associated with 'mutations' in human gene	References
<i>Celsr1</i>	CRN *	CRN	70,110
<i>Dvl1/2</i> or <i>Dvl2/3</i>	CRN	<i>DVL2</i> : Varying types of NTDs, not CRN	111,112
<i>Fuz</i>	Exencephaly	Varying types of NTDs, not exencephaly	113
<i>Fz3/6</i>	CRN	<i>FZD6</i> : Varying types of NTDs, not CRN	114,115
<i>Pk1</i>	None	Varying types of NTDs, not CRN	85
<i>Prk7 (CCK-4)</i>	CRN	No reports	116
<i>Scrib</i>	CRN	CRN	70,117
<i>Sec24b</i>	CRN	No reports	118
<i>Vangl1</i>	None	Varying types of NTDs, not CRN	68,119,120
<i>Vangl2</i>	CRN	Varying types of NTDs, not CRN	69,84,121,122

* CRN: craniorachischisis