

REVIEW

Oesophageal atresia, tracheo-oesophageal fistula, and the VACTERL association: review of genetics and epidemiology

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Oesophageal atresia and/or tracheo-oesophageal fistula are relatively common malformations occurring in approximately 1 in 3500 births. In around half of the cases (syndromic oesophageal atresia), there are associated anomalies, with cardiac malformations being the most common. In the remainder (non-syndromic cases), oesophageal atresia/tracheo-oesophageal fistula occur in isolation. Data from twin and family studies suggest that genetic factors do not play a major role, and yet there are well-defined instances of this malformation where genetic factors clearly are important. This is highlighted by the recent identification of no fewer than three separate genes with a role in the aetiology of oesophageal atresia: those for Feingold syndrome (N-MYC), anophthalmia-oesophageal-genital (AEG) syndrome (SOX2), and CHARGE syndrome (CHD7). Additional support for genetic factors in this malformation comes from chromosomal studies and mouse models. This paper reviews current knowledge of the genetics and epidemiology of the different oesophageal atresia/tracheo-oesophageal fistula syndromes and associations.

factor for OA/TOF, and there are other examples of specific chromosomal imbalances, discussed below, which also predispose to this malformation. Until recently, no genes had been associated with oesophageal atresia in humans. However, three separate genes associated with syndromic OA/TOF in humans have now been identified,^{3–5} making this an exciting time for those interested in the aetiology of this malformation.

This paper reviews current knowledge of the genetics, aetiology, and epidemiology of syndromic and non-syndromic OA/TOF, placing this new information in its overall context.

EMBRYOLOGY

The intimate relationship of the trachea and oesophagus is evident from early embryonic life. The respiratory diverticulum appears at around 4 weeks of age as an outgrowth from the ventral wall of the foregut and invades the surrounding splanchnic mesoderm.

Although there are many references in the literature^{6–8} to the separation of the trachea from the foregut by means of a process of “pinching off” achieved by the existence of lateral tracheo-oesophageal ridges which grow and fuse in the midline, Williams *et al*⁹ have drawn attention to the lack of any direct imaging or reconstruction through histological sections of the tracheo-oesophageal ridges, and in addition have noted the presence of apoptotic bodies at the point of tracheo-oesophageal separation (originally described by Qi and Beasley¹⁰). Both groups of authors suggest that it is the process of apoptosis, with “collapse and fusion of the lateral walls of the foregut”, rather than the growth and fusion of lateral ridges, which causes oesophagus and trachea to separate, although the existence of a tracheo-oesophageal septum arising from fusion of longitudinal ridges within the lumen of the foregut is still postulated by some authors.⁷

ANATOMIC VARIANTS OF OA/TOF

Several anatomic classifications have been proposed (reviewed in Harmon and Coran¹¹); that illustrated in fig 1 is taken from Gross.¹² The incidence of the various types of anomaly is derived from more than 2200 cases in six large series.¹¹ A very detailed classification which corresponds broadly to other schemes but includes other rarer anatomic variants such as membranous atresia, oesophago-bronchial fistula, and oesophageal duplication, has been described.¹³

Oesophageal atresia and tracheo-oesophageal fistula (OA/TOF) are common life-threatening malformations with an incidence of approximately 1 in 3500 births. The aetiology of OA/TOF is unknown in the majority of cases. In approximately half of the cases (syndromic oesophageal atresia), there are other associated anomalies, with cardiac malformations being the most common. These may occur as part of VATER or the VACTERL association (OMIM 192350). In the remaining cases, OA/TOF occur in isolation (non-syndromic oesophageal atresia).

The birth of a child with OA/TOF into a family without a previous history of the condition is associated with a low recurrence risk, of the order of 1%.¹ The twin concordance rate for OA/TOF is likewise low, at around 2.5%.² These data do not indicate a major role for genetic factors in the pathogenesis of OA/TOF, yet there are well-defined instances of the condition where genetic factors are clearly important. Trisomies of chromosomes 18 and 21 are a significant risk

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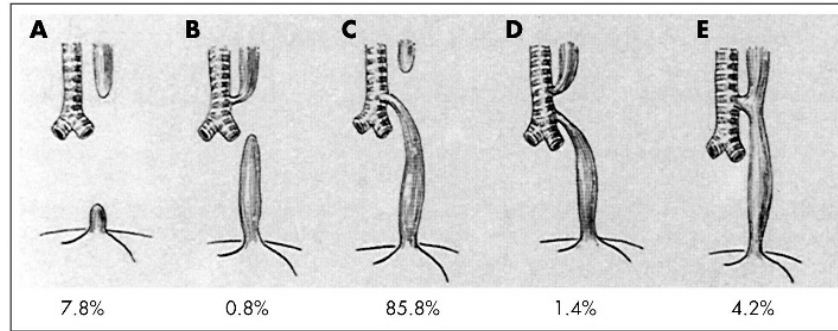


Figure 1 Anatomical classification of anomalies of the oesophagus and trachea, with approximate incidences. (From: Gross RE. *Surgery of infancy and childhood*. Philadelphia, PA: WB Saunders, 1953. Reprinted with permission from Elsevier Press.)

EPIDEMIOLOGY

Data from three large scale epidemiological studies are summarised in table 1. The incidence of OA/TOF is approximately 1 in 3500 births. There is little evidence to support significant geographical or secular variation in the incidence of OA/TOF. Robert *et al*² reported a significantly lower birth frequency (1.82/10 000 births) in Norway, but the birth frequency in Sweden in the same study was 2.67/10 000, and other published data investigating this trend are lacking. No consistent secular trend was identified in the above studies, although Depaeppe *et al*¹⁴ identified a downward trend in birth frequency over time in different regions of Europe. When chromosomal cases are excluded, there is no evidence for a link between OA/TOF and maternal age.

The figures for isolated versus associated OA/TOF (presence of an additional congenital malformation) vary between 38.7%,¹⁵ 45.0%,¹⁴ and 57.3%² (chromosomal cases included). Differences in ascertainment are likely to account for some of the discrepancy. For example, in the Worldwide study,² only those births occurring after 28 weeks' gestation were included. Many early fetal deaths due to multiple

malformations are therefore likely to have been excluded, with the likely effect of inflating the figure for isolated cases.

Data on malformations associated with OA/TOF in these epidemiological studies are summarised in table 1. The malformations most commonly found with OA/TOF are those present in the VACTERL association. These are discussed further in the section on the VACTERL association below.

The data suggest that the incidence of trisomies and other chromosomal imbalances is fairly consistent at between 6 and 10%. The lower figure of 6.3% in the Worldwide study² is again likely to be explicable on the basis of cases excluded prior to 28 weeks' gestation. The total number of cases in infants with trisomy 18 (127) exceeds the number of cases due to trisomy 21 (102) despite the fact that trisomy 18 is much rarer than trisomy 21. This appears to indicate that trisomy 18 may be a greater risk factor for OA/TOF than trisomy 21.

OA/TOF AND TWINNING

Congenital malformations, including OA/TOF, occur more commonly in twins. Mastroiacovo *et al*¹⁶ found that, of 92

Table 1 OA/TOF epidemiological data

	Depaeppe <i>et al</i> ¹⁴	Robert <i>et al</i> ²	Torfs <i>et al</i> ¹⁵
Geographical location	Europe	Worldwide	California
Total births	1 546 889	10 541 994	1 035 384
Ascertainment	Live births, fetal deaths, induced abortions	Live births, still births with gestational age 28 completed weeks or more	Live births and stillbirths
Number of cases	442	2693	292
Incidence/10 000	2.86	2.55	2.82
Isolated cases*	45.0%	57.3%	38.7%
Sex ratio (isolated cases)	62% male	56.5% male	52.2% male
Chromosomal cases			
Trisomy 13	1	2	1
Trisomy 18	21	87	19
Trisomy 21	22	72	8
Other	0	9	1
Total	44 (10.0%)	170 (6.3%)	29 (9.6%)
Associated/syndromal cases†: other malformations			
Cardiac malformation	20.4%	13.2%	34%
Renal malformation	14.0%	4.9%	NS
CNS defect (excluding NTD)	NS	1.4%	NS
Axial skeleton defect	21.2%	6.6%	NS
Limb reduction defect	19.2%	4.7%	NS
Anal atresia/stenosis	11.6%	10.4%	16.4%
Genital anomaly	3.0%	2.9%	NS
Eye malformation	NS	1.2%	NS
Cleft lip/palate	3.4%	2.9%	NS

*Fraction of cases with isolated OA/TOF expressed as a percentage of all cases; †includes chromosome cases. NS, not stated; NTD, neural tube defect.

malformations studied, 39, including OA/TOF, were more common in twins than in singletons. The relative risk for OA/TOF in twins compared with singletons was 2.56 (95% confidence interval 2.01 to 3.25). In one series,¹⁷ the frequency of twinning in patients with OA/TOF was 7% compared with the expected population rate of 2.3%.

The concordance rate in twins is low, suggesting that mechanisms other than genetics are responsible for the occurrence of OA/TOF in twins. In the series reported by Robert *et al.*,² 80 twin pairs were identified, of which just two pairs (2.5%) were concordant, the remaining 78 being discordant. Of the 80 pairs, the sex of the co-twin was known in 50. Forty three were like-sexed (22 male, 21 female) and only seven unlike-sexed. These data may suggest an increased incidence of monozygosity in these twin pairs, although confirmatory data are lacking. Other studies have found similar results for twin pairs.¹⁸

FAMILY STUDIES OF OA/TOF

Warren *et al.*¹⁹ provided the first estimate of offspring risk in patients with OA/TOF. They studied 79 patients who had undergone operations for OA/TOF between 1947 and 1959. Fifteen of these patients had produced a total of 28 children. One of these children had OA/TOF. The sibling recurrence risk was similarly low, with one instance of recurrence in the 130 siblings of the 79 study patients.

McMullen *et al.*²⁰ studied first degree relatives of 140 index cases with OA/TOF, and obtained offspring and sibling recurrence risk figures for VACTERL-type malformations of 2–3% and 1.4%, respectively.

Brown *et al.*²¹ compared the incidence of VACTERL-type malformations in the first degree relatives of OA/TOF cases versus controls. They found that 5.8% of case families versus 3.1% of control families contained at least one first degree relative with one or more of the extended VACTERL components ($p < 0.01$).

HUMAN SINGLE GENE DISORDERS AND OESOPHAGEAL ATRESIA

Feingold syndrome

Feingold syndrome (oculodigitoesophagoduodenal syndrome, OMIM 164280; reviewed by Celli *et al.*²²) is characterised by microcephaly, digital abnormalities, and atresias of the alimentary tract, principally of the oesophagus. Microcephaly occurs in the majority of cases, and may be associated with usually mild learning disability. The digital anomalies are characteristic, involving brachymesophalangy and clinodactyly of the second and fifth digits in the hands, and variable syndactyly of the toes. An affected father and son are shown in fig 2. Inheritance is autosomal dominant, and the gene for the condition was previously mapped to chromosome 2p23.²³

Recently, mutations in the gene N-MYC were shown to cause Feingold syndrome.³ Amplifications of this gene had previously been associated with neuroblastoma,²⁴ and mice with loss of function mutations in the gene had defects in embryonic organogenesis, although not specifically of the oesophagus or trachea.^{25,26} N-MYC was not therefore an obvious candidate. Nonetheless, van Bokhoven and co-workers identified 12 different heterozygous mutations and two whole-gene deletions in N-MYC. All of the mutations occurred in exon 3 of the gene. A role for N-MYC as a regulator of progenitor cell proliferation and differentiation in the mouse lung has recently been identified,²⁷ but the role of this gene in foregut and trachea development has yet to be elucidated.

CHARGE syndrome

OA/TOF is not a major criterion for CHARGE syndrome, which comprises Coloboma, Hear defect, Atresia choanae,

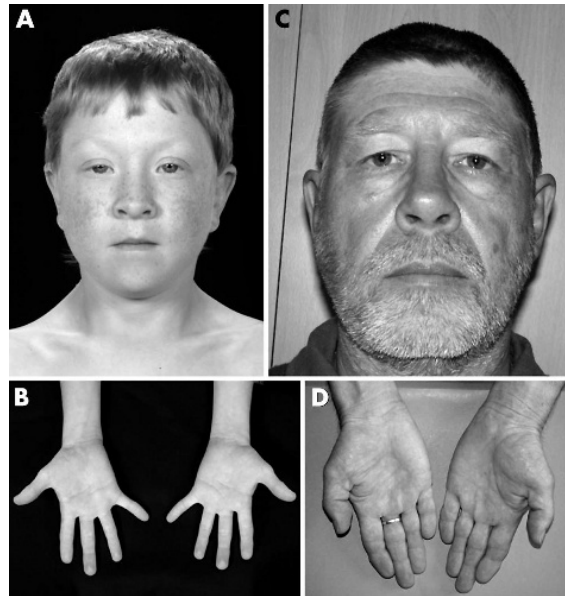


Figure 2 Feingold syndrome. Affected boy (A, B) and his father (C, D). Note short palpebral fissures and periorbital fullness (A), mild bilateral fifth finger clinodactyly (B), short palpebral fissures (C), and bilateral clinodactyly of second and fifth fingers with brachymesophalangy of the second fingers (D). (Reproduced with permission from Shaw-Smith C, Willatt L, Thalange N. *Clin Dysmorphol* 2005;14(3):155–8.)

Retarded growth, Genital hypoplasia and Ear anomalies, but it occurs in about 10% of cases of the syndrome.²⁸ Heterozygous mutations (10) or whole gene deletions (two) of the chromodomain helicase DNA-binding family member CHD7 were recently identified in 12/19 individuals with CHARGE syndrome.⁴ In a more recent clinical survey, oesophageal atresia and/or tracheo-oesophageal fistula were found in 17% of individuals with CHD7 mutations.²⁹

Chromodomain proteins have a role in the epigenetic regulation of heterochromatin function and euchromatic gene expression. One hypothesised role is that they serve to protect the chromatin fibre from changing its epigenetic state.³⁰ Genotype-phenotype and functional studies in humans and model organisms will help to clarify the relationship between CHD7 and CHARGE syndrome.

Anophthalmia-oesophageal-genital syndrome (AEG syndrome)

The association of oesophageal atresia with anophthalmia and genital abnormalities is a rare though well-documented entity in the literature, with fewer than 20 cases reported.^{31,32} Loss of function mutations in SOX2 were previously reported in 4/102 patients with microphthalmia, anophthalmia, or coloboma.³³ Recently, heterozygous SOX2 mutations have been demonstrated in patients with AEG syndrome.⁵ Little is known of the role of SOX2 in foregut and lung development. The chick homologue of SOX2, cSox2, is expressed in the developing foregut, though not more caudally in the gut tube. During morphogenesis, cSox2 expression levels fall in the developing lung primordium as it invades the surrounding mesenchyme.³⁴ The precise role of SOX2 in relation to the pathogenesis of OA/TOF remains to be elucidated.

Fanconi anaemia and OA/TOF

OA/TOF, as well as other gastro-intestinal atresias (anal, duodenal) is a well-documented component of the malformation spectrum associated with Fanconi anaemia.

Gastro-intestinal atresias have been reported in 14% of cases of Fanconi anaemia.³⁵ Other malformations falling within the VACTERL spectrum also occur: skeletal (71%), cardiac (13%), and renal (34%).³⁵ The birth frequency of OA/TOF is approximately 1 in 3000, that of Fanconi anaemia approximately 1 in 300 000, and that of Fanconi anaemia presenting with a gastro-intestinal atresia another order of magnitude lower. Clearly, therefore, the prior risk of FA in a child born with OA/TOF must be very small, and the contribution of FA to the aetiology of OA/TOF likewise small. Nonetheless, it is possible that mutations in one of the FANC genes are responsible for OA/TOF in a proportion of individuals with this malformation. Some of these individuals may not be penetrant for the haematological phenotype. Now that the majority of the FANC genes have been identified,³⁶⁻³⁷ this hypothesis is testable. The possible aetiological basis for the relationships between DNA repair disorders and human malformations has recently been discussed.³⁸

Multiple gastro-intestinal atresias (MGIA)

There are several reports of a lethal syndrome of multiple gastro-intestinal atresias in the oesophagus, small intestine, and biliary system.³⁹⁻⁴¹ Parental consanguinity and sibling recurrence in these families point to autosomal recessive inheritance. No mapping studies have been performed to date. This condition appears to be distinct from the syndrome of hereditary multiple intestinal atresias (HMIA), also considered to be autosomal recessive,⁴² which does not involve the oesophagus. In HMIA, septal atresias with incomplete separation of the atretic segments occur throughout the stomach and large bowel.

Oesophageal atresia and chromosomal abnormalities

The association between OA/TOF and trisomy for chromosomes 18 and 21 has already been discussed above in the section on epidemiology.

There is a weak association between OA/TOF and the 22q11 deletion syndrome. Digilio *et al*⁴³ found a single case of 22q11 deletion syndrome in a series of 15 patients with syndromic oesophageal atresia, and there are other case reports in the literature.⁴⁴

There appears to be a link between OA/TOF and deletions at chromosome 17q22q23.3. Marsh *et al*⁴⁵ reported a single case and reviewed two others, in all three of whom OA/TOF and congenital heart defects were present. In addition, these patients had dysmorphic facial features and minor skeletal malformations. This chromosomal region contains the genes TBX2 and TBX4. Mice haploinsufficient for the Tbx2 gene have been shown to have atrioventricular septal defects, though not OA/TOF.⁴⁶ A study in chick⁴⁷ showed that ectopic expression of Tbx4 in foregut visceral mesoderm caused failure of formation of tracheo-oesophageal septum. Hitherto, haploinsufficiency or mutations in these two genes have not been associated with OA/TOF in humans, except in the context of the large chromosomal deletions discussed above.

Patients with deletions at chromosome 13q32 have been reported to have multiple elements of the VACTERL association. This possible link is discussed further in the section below on the VACTERL association.

Disruption of the gene BPAG1 was recently reported in an individual with a 6;15 reciprocal translocation and oesophageal atresia.⁴⁸

OESOPHAGEAL ATRESIA AND TERATOGENS

Clementi *et al*⁴⁹ reported a case of congenital anomalies, including oesophageal atresia, in a child exposed to methimazole in the first trimester of pregnancy and drew attention to two previous cases with the same association.⁵⁰

THE VACTERL ASSOCIATION

OA/TOF is a component of the VACTERL association, which comprises Vertebral defects, Anal atresia, Cardiac defects, Tracheo-Esophageal fistula, Renal malformations, and Limb defects. The association was first proposed by Quan and Smith in 1972,⁵¹ initially as the acronym VATER, where the letter "R" stood for "radial dysplasia". Subsequently, the acronym was expanded to include cardiac and renal defects.⁵² Both terms remain in use in the literature, illustrating the problem of defining the clinical features that comprise the association. In this review, the acronym VACTERL is used except where VATER is appropriate for historical reasons.

Earlier studies⁵³⁻⁵⁷ confirmed the non-random occurrence of the association but did not specifically address the question of which of the more peripheral elements of the association should be included within its definition. More recent studies⁵⁸ have attempted to address this issue by taking, as far as possible, an approach free of ascertainment bias. The results⁵⁸ indicated a distinct group of malformations corresponding with the VACTERL association, with an "upper" group associated with heart malformations and a "lower" group associated with renal malformations. The authors acknowledged the difficulty of controlling for possible bias in the way that patients are investigated which might tend to confirm some associations (oesophageal atresia, upper costo-vertebral defects, cardiac defects), but not others where the anatomic locations are more disparate.

There are very few published series of VACTERL patients in which the clinical phenotypes have been carefully delineated, perhaps unsurprisingly in view of the difficulties of definition, and the risk of inadvertent inclusion of cases with a syndromic diagnosis. Weaver *et al*⁵⁹ reported a series of 46 patients.

One of the key difficulties in studies of this nature is the evolving nature of our knowledge of syndromes which may overlap with or resemble the VACTERL association. Feingold syndrome, CHARGE syndrome, 22q11 deletion syndrome, Townes-Brocks syndrome, and Pallister-Hall syndrome (all discussed further below) show some phenotypic overlap with the VACTERL association, and most series of patients ascertained by epidemiological means are not divided into subgroups according to confirmed or possible syndromic diagnoses.

Individuals with the VACTERL association do not typically have facial dysmorphic features, learning disability, or abnormalities of growth, including head circumference. For these individuals, sibling and offspring recurrence risks are low, and are usually quoted as being around 1%. There are very few instances of recurrence of the VACTERL association in the literature. However, two examples are Nezarati and McLeod⁶⁰ and Auchterlonie and White.⁶¹

Where dysmorphic features, growth abnormalities, and/or learning disability are present, a syndromic diagnosis or chromosomal abnormality may be the underlying cause, as discussed in the following section.

SINGLE GENE DISORDERS RESEMBLING THE VACTERL ASSOCIATION

An overview of single gene disorders with features in common with the VACTERL association is presented in table 2.

Feingold syndrome

The overlap between Feingold syndrome and the VACTERL association has been discussed in detail by Celli *et al*.²² As well as oesophageal atresia which occurs in around 25% of affected individuals, other VACTERL-type malformations occur in Feingold syndrome, including vertebral malformations, anal atresia, and cardiac, renal, and limb malforma-

Table 2 Phenotypic overlap with the VACTERL association: disorders of known genetic aetiology

Name	OMIM	Locus	Gene name	Major clinical features	Features occurring in syndrome which are not part of VACTERL	VACTERL components absent from syndrome	References
Feingold	164280	2p23-p24	N-MYC	Microcephaly, gastro-intestinal atresias, cardiac malformations, renal malformations	Microcephaly, learning difficulties, facial dysmorphism	Vertebral anomalies; limb malformations are not of VACTERL type	van Bokhoven <i>et al.</i> ³ Celli <i>et al.</i> ²²
CHARGE	214800	8q12	CHD7	Coloboma, heart defect, atresia choanae, retarded growth, genital anomaly, ear anomaly	Coloboma, ear and genital anomalies	Anal atresia, limb anomalies	Vissers <i>et al.</i> ⁴
Fanconi	607139 300515 227645 605724 227646 600901 603467 602956 605882	16q24.3 Xp22.31 9q22.3 13q12.3 3p25.3 6p21-22 11p15 9p13 17q22	FANCA FANCB (FAAP95) FANCC FANCD1 (BRCA2) FANCD2 FANCE FANCF FANCG FANCI (BRIP1)	Susceptibility to cancer, short stature, congenital malformations	Susceptibility to cancer, café au lait patches, microcephaly, growth restriction	None	Tischkowitz and Hodgson, ³⁶ Meetei <i>et al.</i> , ³⁷ Levrin <i>et al.</i> ⁶²
22q11 deletion syndrome	188400	22q11	TBX1	Cleft palate, heart defect, thymic abnormality, facial dysmorphism, hypocalcaemia	Cleft palate, hypocalcaemia, thymic abnormality, facial dysmorphism	Vertebral anomalies, anal atresia, limb malformations	Ryan <i>et al.</i> ⁶³
Townes-Brocks	107480	16q21.1	SALL1	External ear anomalies, preaxial polydactyly, triphalangeal thumbs, imperforate anus, renal malformations	External ear anomalies, hearing loss	OA/TOF, cardiac malformations, vertebral anomalies	Powell and Michaelis ⁶⁴
Pallister-Hall	146510	7p14.1	GLI3	Hypothalamic hamartoma, polydactyly, cardiac and renal defects	Hypothalamic hamartoma, craniofacial dysmorphism	OA/TOF, vertebral anomalies	Johnston <i>et al.</i> ⁶⁵

tions.²² There are also significant differences between the two conditions: Feingold syndrome is dominantly inherited, whereas the VACTERL association occurs sporadically. Microcephaly, minor facial dysmorphism, and learning difficulties occur in Feingold syndrome but not classically in the VACTERL association. Van Bokhoven *et al.*³ tested eight individuals with the VACTERL association; no mutations in the N-MYC gene were identified.

CHARGE syndrome

CHARGE syndrome may cause diagnostic difficulty, particularly where few features are present and the more characteristic features of the syndrome (coloboma, choanal atresia) are absent. Identification of the causative gene⁴ means that it will be possible to delineate the full phenotypic spectrum. It is likely that some cases previously classified clinically as the VACTERL association will prove to have CHD7 mutations, although this remains to be seen.

Fanconi anaemia and the VACTERL association

The apparently Mendelian segregation of VACTERL in association with hydrocephalus (VACTERL-H) is a rarely reported but distinct entity. X linked⁶⁶⁻⁶⁸ and recessive forms⁶⁹ have been described.

Cox *et al.*⁶⁹ reported a dizygotic twin pair with features of VACTERL-H and no evidence of increased chromosome breakage on routine testing. Homozygous mutations in the FANCC gene were detected in both twins, providing the first molecular evidence of a link between VACTERL-H and Fanconi anaemia.

OA/TOF, as well as duodenal atresia, have been reported in several family members in pedigrees with VACTERL-H and apparently X linked inheritance. Some of these families have

contained individuals with an increased incidence of chromosome breakages, diagnostic of Fanconi syndrome. The family reported by Wang *et al.*⁶⁶ contained three such individuals; but breakages were not found in a single case in a pedigree containing four affected individuals reported by Lomas *et al.*⁶⁸ A gene responsible for X linked Fanconi anaemia has recently been identified;³⁷ it will be interesting to test the possible role of this gene in X linked VACTERL-H families.

In one series, VACTERL-type clinical presentations accounted for 5% of all cases of Fanconi anaemia and there was over-representation of complementation groups D1, E, and F in this group.⁷⁰ Faivre *et al.*⁷¹ reported a series of 13 FA cases presenting with VACTERL-type malformations, all of whom had radial ray anomalies, and 12 out of 13 of whom had an additional FA feature (café au lait patches, microcephaly, growth retardation, or dysmorphism). They suggested that chromosome breakage studies should be performed in patients in this clinical group.

Townes-Brocks syndrome

Townes-Brocks syndrome (reviewed in Powell and Michaelis⁶⁴) is an autosomal dominant disorder, the main manifestations of which are external ear anomalies, preaxial polydactyly, imperforate anus, and renal malformations. Oesophageal atresia is not a reported feature; there may be an association with congenital heart disease but this is controversial.⁶⁴ The most common limb defects are triphalangeal thumb and preaxial polydactyly. Hypoplasia of the thumb and radial bone are not features of this syndrome. Structural vertebral anomalies have not been reported. Mutations in the SALL1 gene at 16q12.1 are responsible for Townes-Brocks syndrome.⁷²

Pallister-Hall syndrome

Anal atresia and limb malformations are features of this dominantly inherited syndrome,⁶⁵ though in practice there should be little difficulty in distinguishing it from the VACTERL association as hypothalamic hamartoma and neurological complications are cardinal features, and the limb malformations are not of the VACTERL type. Pallister-Hall syndrome is due to mutations in the *GLI3* gene,⁶⁵ and, given the mouse knockout phenotypes discussed below, it is of interest that laryngeal clefts and atypical lung lobation are also features of this syndrome.

OTHER CONDITIONS WITH PHENOTYPIC OVERLAP WITH THE VACTERL ASSOCIATION

22q11 deletion syndrome may show significant clinical overlap with the VACTERL association. Oesophageal atresia has been reported⁴³ and may occur in combination with cardiac and renal malformations, though limb and vertebral anomalies and anal atresia are not recognised features.

There is a recognised overlap between the VACTERL association and hemifacial microsomia or oculo-auriculo-vertebral spectrum.⁷³⁻⁷⁴ Although ear and eye malformations are typical of hemifacial microsomia, vertebral anomalies, congenital heart defects, and oesophageal atresia are also described.⁷⁴⁻⁷⁵ The aetiology of hemifacial microsomia is poorly understood. Familial cases are described and linkage to chromosome 14q32 has been assigned on the basis of a large dominant pedigree.⁷⁶

There are three reports in the literature of an association between VACTERL and tibial aplasia.⁷⁷⁻⁷⁸ All three cases had OA/TOF, but additional features (malformed ears, cleft lip/palate) were present in one case.

Reardon *et al*⁷⁹ reported a mutation in the *PTEN* gene in a patient with macrocephaly, tracheo-oesophageal fistula, and bilateral thumb hypoplasia.

TERATOGENS ASSOCIATED WITH THE VACTERL ASSOCIATION

A two- to threefold increase in the incidence of multiple congenital malformations is recognised in the children of diabetic mothers.⁸⁰ Most characteristically, these malformations appear to affect the caudal part of the body, although central nervous system anomalies, oesophageal atresia, congenital heart defects, and rib and vertebral anomalies are all described, indicating a clear overlap with the VACTERL association.

CHROMOSOMAL IMBALANCES IN THE VACTERL ASSOCIATION

Walsh *et al*⁸¹ reported a case of peno-scrotal transposition associated with all six VACTERL components, in a patient with distal chromosome 13q deletion. Peno-scrotal transposition is a rarely noted finding in the VACTERL association.⁸² Walsh *et al*⁸¹ performed a detailed review of the literature on deletions of the distal long arm of chromosome 13 and identified 147 patients with this chromosomal abnormality. Of these, five had four VACTERL elements, 12 had three elements, 23 had two elements, and 28 had one element, although only one patient, that reported by Walsh *et al*⁸¹ had OA/TOF (oesophageal atresia and a tracheo-oesophageal fistula in this instance). As well as components of the VACTERL association, some of these patients also had CNS malformations, including holoprosencephaly, anencephaly, hydranencephaly, callosal agenesis, neural tube defects, and ventriculomegaly; in addition there were often other features such as the diagnosis of the VACTERL association was not postulated in the original publications.⁸³⁻⁸⁶ The review included some patients previously investigated in a study by Brown *et al*⁸⁷ which had identified a critical region for

major malformations at chromosome 13q32. Mutations in the *ZIC2* gene, which is at chromosome 13q32, are associated with holoprosencephaly, suggesting that CNS malformations in patients with distal 13q deletions may be due to haploinsufficiency of this gene.

Cinti *et al*⁸⁸ reported a supernumerary ring chromosome 12 in a patient with an anorectal malformation, vertebral anomalies, and an absent kidney. There are very few other reports of chromosomal abnormalities in patients with the VACTERL association.⁸⁹⁻⁹⁰

OA/TOF, VACTERL, AND ASSOCIATIONS

The term "association" was first used specifically with respect to the VATER association by Quan and Smith.⁵¹ Lubinsky⁹¹ gave the following definition of associations: "Associations are derivatives of causally non-specific disruptive events acting on developmental fields". In the case of errors of blastogenesis, the developmental field constitutes the entire embryo.⁹² Opitz⁹² gave a modified definition of associations: "Associations represent the *idiopathic* occurrence of multiple congenital anomalies during blastogenesis" (italics here and later in this section are those of C.S.S.). The key concept is the implication that *different* causal factors acting at particular stages in development give rise to *similar* patterns of malformations. Martinez-Frias *et al*⁹³ advocated the use of the term *polytopic field defect* to replace the term *association* in this context. In the case of the VACTERL association, causative perturbations may be of known genetic origin, in which case they give rise to syndromes (see table 2), and the term association is no longer applicable; or they may be due to environmental agents (teratogens), in which case they remain idiopathic. The underlying causes of the sporadic forms of the VACTERL association for the most part remain to be elucidated, with the exception of those instances due to maternal diabetes. According to the model proposed by Lubinsky, single malformations derived from teratologic events can be part of the same spectrum as associations.⁹¹ In this sense, oesophageal atresia with or without tracheo-oesophageal fistula, and sporadic forms of the VACTERL association can, for the purposes of hypothesis testing, be considered to be two different points on a spectrum constituting a single overarching entity.

KNOCK-OUT MICE FEATURING TRACHEO-OESOPHAGEAL MALFORMATIONS

Mice deficient in genes in the sonic hedgehog pathway, including sonic hedgehog itself, exhibit OA/TOF. Mice homozygously deficient for sonic hedgehog display multiple malformations including oesophageal atresia/stenosis and tracheo-oesophageal fistula.⁹⁴⁻⁹⁶ Mice homozygously deficient for the *Gli2* gene likewise exhibit multiple anomalies, including a foregut defect consisting of hypoplastic oesophagus and trachea with oesophageal stenosis.⁹⁷ Haploinsufficiency of *Gli3* on the *Gli2*^{-/-} background produces a more severe defect with OA/TOF.⁹⁷ *Gli2*^{-/-} *Gli3*^{-/-} mice have a severe phenotype with absence of oesophagus, trachea, and lungs.⁹⁷

The winged helix transcription factor *foxf1* is activated by sonic hedgehog signalling and mice haploinsufficient for *foxf1* display narrowing of the oesophagus and trachea, oesophageal atresia, and tracheo-oesophageal fistula.⁹⁸

There is one report describing oesophageal abnormalities associated with the targeted disruption of a homeobox gene. Mice haploinsufficient for the homeobox gene *hoxc4* had complete occlusion of the oesophageal lumen, with extensive disorganisation of the oesophageal musculature, although not oesophageal atresia.⁹⁹

Mice homozygously deficient for the homeodomain transcription factor *nkx2.1* show a severe tracheo-oesophageal

phenotype with a common lumen that connects the pharynx to the stomach. In addition, the lungs are profoundly hypoplastic with absence of distal structures.¹⁰⁰ Finally, failure of separation of the oesophagus and trachea is seen in mouse embryos doubly homozygous for mutations in the retinoic acid receptor genes *RAR α* and *RAR β* .¹⁰¹

MOUSE MODELS OF THE VACTERL ASSOCIATION

Elements suggestive of, if not identical to, those seen in the VACTERL association are also present in some of the mouse models.¹⁰² *Shh*^{-/-} mice display, in addition to the defects of trachea and oesophagus, absence of the vertebral column, persistent cloaca with abnormalities of heart looping, solitary kidney, and truncating limb malformations. *Gli2*^{-/-} mice have absent vertebral bodies,¹⁰³ imperforate anus,¹⁰⁴ and limb hypoplasia,¹⁰³ though no renal or cardiac abnormalities. *Gli3*^{-/-} mice have abnormal development of neural arches,¹⁰³ anal stenosis,¹⁰⁴ and polydactyly,¹⁰³ though no renal, cardiac, or tracheo-oesophageal malformations. *Gli2*^{-/-} *Gli3*^{+/-} mice display lack of a vertebral column, persistent cloaca, heart looping defects, horseshoe kidney, and polydactyly.¹⁰²

In humans, mutations in *SHH* are associated with holoprosencephaly,¹⁰⁵ and mutations in *GLI3* with Pallister-Hall syndrome.⁶⁵ There are no published data on the possible roles of these genes in patients with syndromic OA/TOF, to the author's knowledge, although laryngeal clefts, which may be associated with tracheo-oesophageal fistula, are a feature of Pallister-Hall syndrome.⁶⁵

OTHER ANIMAL MODELS OF OESOPHAGEAL ATRESIA

Administration of adriamycin to rats at embryonal day 10.5 results in oesophageal atresia and other malformations including those of the VACTERL association.¹⁰⁶ Abnormalities of the notochord occur in this model,¹⁰⁷ and at the molecular level, abnormalities of expression of genes in the sonic hedgehog pathway have been described.^{108, 109}

EVALUATION OF THE PATIENT WITH OA/TOF

Oesophageal atresia is, both clinically and aetiologically, a very heterogeneous condition, and this review highlights the diversity of aetiological factors that can lead to this malformation. The following considerations may aid in diagnosis and in genetic counselling:

- History: exposure to teratogens, particularly methimazole, in pregnancy; enquire specifically about maternal diabetes in pregnancy.
- Family history with special attention to individuals in the family with OA/TOF, other GI atresia, cardiovascular or renal malformations, late pregnancy losses, early post-natal deaths, polyhydramnios, microcephaly, or learning disability. All of these may suggest Feingold syndrome.
- Clinical examination with special attention to head circumference and examination of digits (microcephaly and digital malformations as described in fig 1 may indicate Feingold syndrome), examination of eyes (coloboma may suggest CHARGE syndrome; anophthalmia/microphthalmia may point to AEG syndrome). Dysmorphic features and retarded growth may point to CHARGE syndrome or a chromosomal imbalance such as a trisomy or 22q11 deletion syndrome. Features suggestive of Fanconi anaemia (café au lait patches, microcephaly, growth retardation) should specifically be sought.⁷¹
- Investigations: karyotype for the exclusion of trisomies 18 and 21, FISH for 22q11 deletion (especially when a cardiac defect is present), array-CGH where a chromosomal abnormality is suggested by the clinical features and karyotype and FISH studies are normal. Chromosome

breakage studies for Fanconi anaemia should be considered where a VACTERL-type presentation is combined with other suggestive features (see above). Mutation analysis of *N-MYC*, *CHD7*, or *SOX2* may be sought where the phenotype is suggestive. All patients with OA/TOF should have an echocardiogram; limb or vertebral X rays may be performed according to the clinical picture; renal USS is suggested where there are other features of the VACTERL association.

Genetic counselling

The identification of genes associated with oesophageal atresia offers the prospect of improvements in genetic counselling for this disorder. Even after successful surgical treatment, OA/TOF is associated with significant morbidity and where associated with other congenital malformations, there is appreciable mortality.¹¹⁰ Many parents of affected children, and affected individuals who would like to have children, will welcome the prospect of improved genetic diagnosis that the identification of the Feingold syndrome gene in particular is likely to bring.

The combination of OA/TOF with microcephaly and digital malformations makes Feingold syndrome highly recognisable if the diagnosis is considered, but easily missed if these subtle findings are not specifically sought. Other clinical features may occur; a detailed review is provided by Celli *et al.*²²

The figure of approximately 1% for sibling and offspring recurrence risk, which comes from the study of Warren *et al.*,¹⁹ is still quoted in the literature¹ although McMullen *et al.*²⁰ gave a slightly higher figure of 2–3% for offspring recurrence risk. Neither study makes reference to the possibility of Feingold syndrome as a possible explanation for familial recurrence of oesophageal atresia. In the earlier study,¹⁹ sibling and offspring recurrences occurred in the same family, and it is possible that this family represents an example of Feingold syndrome. In any family where there is a recurrence of OA/TOF, Feingold syndrome should be considered.

For the VACTERL association, the quoted recurrence risk appears low.¹ One study²⁰ found an increased incidence of VACTERL-type malformations in first degree relatives of individuals with OA/TOF versus controls, but the recurrence risk specifically for those individuals with the VACTERL association has not been formally studied to the author's knowledge.

DISCUSSION

The recent identification of three separate genes with a role in the genesis of OA/TOF is exciting for those interested in understanding the aetiology of this malformation, and for those who provide genetic counselling. Available epidemiological and family data do not point to a strong role for genetic factors in OA/TOF. The recurrence risk is quoted at 1% or less,¹ and the twin concordance rate is very low, of the order of 2.5%.² These data appear to suggest that, in the majority of cases, the aetiological factors in this malformation are non-genetic. Against this, the existence of familial forms of oesophageal atresia have been known for many years, and likewise ample data, reviewed above, indicate that chromosomal imbalances may predispose to its occurrence. In mice, evidence for the involvement of genes in the sonic hedgehog pathway in normal oesophago-tracheal development is very strong, and it will be interesting to study the possible contribution of genes in this pathway to malformations of these structures in humans.

It is clear that these new data present an opportunity for further teasing out the aetiological mechanisms in OA/TOF. As van Bokhoven *et al.*³ suggest, the role of *N-MYC* in other forms of OA/TOF besides Feingold syndrome should be explored. The same considerations apply to the *CHD7* and

SOX2 genes, and, further, a "panel" of oesophageal atresia genes can be envisaged which could also include the *Fanconi* genes as well as members of the sonic hedgehog pathway, for the high-throughput screening of patients with syndromic forms of oesophageal atresia. As well as looking for mutations in the coding sequences of these genes, it will be important to search for copy number changes. The new technique of exon based array CGH¹¹¹ provides an opportunity to examine copy number changes in a large number of exons simultaneously, thus making high-throughput screening an attractive possibility.

It is likely that the array based technologies which have been successful in identifying submicroscopic chromosomal imbalances in individuals with learning disability and dysmorphic features^{112–113} will add to the figure of approximately 10% of OA/TOF due to chromosomal imbalances. Two approaches will be useful here: the refinement of existing loci by use of high resolution arrays; and the discovery of new imbalances by means of whole genome array CGH at 1 Mb or tile path resolution. Children with OA/TOF due to a chromosomal imbalance often have a severe phenotype, with significant mortality particularly when other malformations and low birth weight are present.¹¹⁰ This includes children with trisomies 13 and 18 as well as other chromosomal imbalances reviewed above. As well as checking the G-banded karyotype in these children, it will be increasingly helpful to store a DNA sample for future genetic studies.

Concerning embryological studies, there is further scope for detailed molecular and cellular studies of the process of separation of trachea and oesophagus in model organisms. As yet there have been no concerted studies in model organisms to try to characterise the transcriptional regulatory pathways involved in this process, as has been carried out for the early stages of liver development, for example.^{114–115} Studies of this nature are now feasible and are likely to identify other genes that play a role in this important stage of development.

The refinement of our knowledge of genetic aetiologies in OA/TOF is likely to have implications for future epidemiological studies. One goal of epidemiological research in this area is to try to identify geographical or temporal trends in the birth frequency of OA/TOF in order to gain clues about possible contributing environmental factors. It is likely that the data in previous studies have been confounded by inclusion of individuals with unappreciated genetic aetiologies. These patients could be excluded from future studies of the epidemiology of oesophageal atresia, helping to refine our currently very limited understanding of the non-genetic factors which may contribute to this malformation.

Most significantly, the identification of new genes with a role in the pathogenesis of oesophageal atresia will help to stimulate further research in, and provide genetic counselling for, this distressing and still poorly understood malformation.

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REFERENCES

- Harper PS. *Practical genetic counselling*, 6th ed. London: Arnold, 2004.
- Robert E, Mutchinick O, Mastroiacovo P, Knudsen LB, Dalveit AK, Castilla EE, Lancaster P, Kallen B, Cocchi G. An international collaborative study of the epidemiology of oesophageal atresia or stenosis. *Reprod Toxicol* 1993;**7**:405–21.
- van Bokhoven H, Celli J, van Rieuwijk J, Rinne T, Claudemans B, van Beusekom E, Rieu P, Newbury-Ecob RA, Chiang C, Brunner HG. MYCN haploinsufficiency is associated with reduced brain size and intestinal atresias in Feingold syndrome. *Nat Genet* 2005;**37**:465–7.
- Vissers LE, van Ravenswaaij CM, Admiraal R, Hurst JA, de Vries BB, Janssen IM, van der Vliet WA, Huys EH, de Jong PJ, Hamel BC, Schoenmakers EF, Brunner HG, Veltman JA, van Kessel AG. Mutations in a new member of the chromodomain gene family cause CHARGE syndrome. *Nat Genet* 2004;**36**:955–7.
- FitzPatrick DR, Magee A, Fiedler Z, Turnpenny P, Schneider A, Messina M, Hever A, Williamson KA, van Heyningen V. Mutations in *SOX2* cause Rogers syndrome (anophthalmia, tracheo-oesophageal fistula and genitourinary anomalies). The American Society of Human Genetics Annual Meeting 2004, session 54, 190.
- Sadler T. *Langman's medical embryology*, 8th ed. Baltimore: Lippincott Wilkins and Williams, 2000.
- Kluth D, Fiegel H. The embryology of the foregut. *Semin Pediatr Surg* 2003;**12**:3–9.
- Felix JF, Keijzer R, van Dooren MF, Rottier RJ, Tibboel D. Genetics and developmental biology of oesophageal atresia and tracheo-oesophageal fistula: lessons from mice relevant for paediatric surgeons. *Pediatr Surg Int* 2004;**20**:731–6.
- Williams AK, Quan QB, Beasley SW. Three-dimensional imaging clarifies the process of tracheoesophageal separation in the rat. *J Pediatr Surg* 2003;**38**:173–7.
- Qi BQ, Beasley SW. Stages of normal tracheo-bronchial development in rat embryos: resolution of a controversy. *Dev Growth Differ* 2000;**42**:145–53.
- Harmon CM, Coran AG. Congenital anomalies of the esophagus. In: O'Neill, James A, et al. *Pediatric surgery*, 5th ed. St Louis, MO: Mosby, 1998:941–67.
- Gross RE. *Surgery of infancy and childhood*. Philadelphia, PA: WB Saunders, 1953.
- Kluth D. Atlas of esophageal atresia. *J Pediatr Surg* 1976;**11**:901–19.
- Dolpepe A, Dolk H, Lechat MF. The epidemiology of tracheo-oesophageal fistula and oesophageal atresia in Europe. EUROCAT Working Group. *Arch Dis Child* 1993;**68**:743–8.
- Torfs CP, Curry CJ, Bateson TF. Population-based study of tracheoesophageal fistula and esophageal atresia. *Teratology* 1995;**52**:220–32.
- Mastroiacovo P, Castilla EE, Arpino C, Botting B, Cocchi G, Goujard J, Marinacci C, Merlob P, Metneki J, Mutchinick O, Ritvanen A, Rosano A. Congenital malformations in twins: an international study. *Am J Med Genet* 1999;**83**:117–24.
- Bankier A, Brady J, Myers NA. Epidemiology and genetics. In: Beasley SW, Myers NA, Auld AW, eds. *Oesophageal atresia*. London: Chapman and Hall, 1991:19–29.
- Orford J, Glasson M, Beasley S, Shi E, Myers N, Cass D. Oesophageal atresia in twins. *Pediatr Surg Int* 2000;**16**:541–5.
- Warren J, Evans K, Carter CO. Offspring of patients with tracheo-oesophageal fistula. *J Med Genet* 1979;**16**:338–40.
- McMullen KP, Kames PS, Moir CR, Michels VV. Familial recurrence of tracheoesophageal fistula and associated malformations. *Am J Med Genet* 1996;**63**:525–8.
- Brown AK, Roddam AW, Spitz L, Ward SJ. Oesophageal atresia, related malformations, and medical problems: a family study. *Am J Med Genet* 1999;**85**:31–7.
- Celli J, van Bokhoven H, Brunner HG. Feingold syndrome: clinical review and genetic mapping. *Am J Med Genet A* 2003;**122**:294–300.
- Celli J, van Beusekom E, Hennekam RC, Gallardo ME, Smeets DF, de Cordoba SR, Innis JW, Frydman M, Konig R, Kingston H, Tolmie J, Govaerts LC, van Bokhoven H, Brunner HG. Familial syndromic esophageal atresia maps to 2p23–p24. *Am J Hum Genet* 2000;**66**:436–44.
- Reiter JL, Brodeur GM. High-resolution mapping of a 130-kb core region of the MYCN amplicon in neuroblastomas. *Genomics* 1996;**32**:97–103.
- Stanton BR, Perkins AS, Tessarollo L, Sassoon DA, Parada LF. Loss of N-myc function results in embryonic lethality and failure of the epithelial component of the embryo to develop. *Genes Dev* 1992;**6**:2235–47.
- Sawai S, Shimono A, Wakamatsu Y, Palmes C, Hanaoka K, Kondoh H. Defects of embryonic organogenesis resulting from targeted disruption of the N-myc gene in the mouse. *Development* 1993;**117**:1445–55.
- Okubo T, Knoepfler PS, Eisenman RN, Hagan BL. Nmyc plays an essential role during lung development as a dosage-sensitive regulator of progenitor cell proliferation and differentiation. *Development* 2005;**132**:1363–74.
- Tellier AL, Cormier-Daire V, Abadie V, Amiel J, Sigaudy S, Bonnet D, de Lonlay-Debeney P, Morrisseau-Durand MP, Hubert P, Michel JL, Jan D, Dollfus H, Baumann C, Labrune P, Lacombe D, Philip N, LeMerrer M, Briard ML, Munnich A, Lyonnet S. CHARGE syndrome: report of 47 cases and review. *Am J Med Genet* 1998;**76**:402–9.
- Jongmans M, Admiraal R, van der Donk K, Vissers L, Baas A, Kapusta L, van Hagen JM, Donnai D, de Ravel T, Veltman J, Geurts van Kessel A, de Vries B, Brunner H, Hoefsloot L, van Ravenswaaij C. CHARGE syndrome: the phenotypic spectrum of mutations in the *CHD7* gene. *J Med Genet*, 2005 Oct 14; [Epub ahead of print].
- Cavalli G, Paro R. Chromo-domain proteins: linking chromatin structure to epigenetic regulation. *Curr Opin Cell Biol* 1998;**10**:354–60.
- Hill CJ, Pilz DT, Harper PS, Castle B, Williams TH. Anophthalmia-oesophageal-genital syndrome: a further case to define the phenotype. *Am J Med Genet A* 2005;**132**:57–9.
- Shah D, Jones R, Porter H, Turnpenny P. Bilateral microphthalmia, esophageal atresia, and cryptorchidism: the anophthalmia-oesophageal-genital syndrome. *Am J Med Genet* 1997;**70**:171–3.

- 33 **Fantes J**, Ragge NK, Lynch SA, McGill NI, Collin JR, Howard-Peebles PN, Hayward C, Vivian AJ, Williamson K, van Heyningen V, FitzPatrick DR. Mutations in SOX2 cause anophthalmia. *Nat Genet* 2003;**33**:461–3.
- 34 **Ishii Y**, Rex M, Scotting PJ, Yasugi S. Region-specific expression of chicken Sox2 in the developing gut and lung epithelium: regulation by epithelial-mesenchymal interactions. *Dev Dyn* 1998;**213**:464–75.
- 35 **Dokal I**. The genetics of Fanconi's anaemia. *Baillieres Best Pract Res Clin Haematol* 2000;**13**:407–25.
- 36 **Tischkowitz MD**, Hodgson SV. Fanconi anaemia. *J Med Genet* 2003;**40**:1–10.
- 37 **Meetei AR**, Levitus M, Xue Y, Medhurst AL, Zwaan M, Ling C, Roomans MA, Bier P, Hoatlin M, Pals G, de Winter JP, Wang W, Joenje H. X-linked inheritance of Fanconi anemia complementation group B. *Nat Genet* 2004;**36**:1219–24.
- 38 **Hales BF**. DNA repair disorders causing malformations. *Curr Opin Genet Dev* 2005;**15**:234–40.
- 39 **Gentile M**, Fiorente P. Esophageal, duodenal, rectoanal and biliary atresia, intestinal malrotation, malformed/hypoplastic pancreas, and hypospadias: further evidence of a new distinct syndrome. *Am J Med Genet* 1999;**87**:82–3.
- 40 **Anneren G**, Meurling S, Lilja H, Wallander J, von Döbeln U. Lethal autosomal recessive syndrome with intrauterine growth retardation, intra- and extrahepatic biliary atresia, and esophageal and duodenal atresia. *Am J Med Genet* 1998;**78**:306–7.
- 41 **Martinez-Frias ML**, Frias JL, Galan E, Domingo R, Paisan L, Blanco M. Tracheoesophageal fistula, gastrointestinal abnormalities, hypospadias, and prenatal growth deficiency. *Am J Med Genet* 1992;**44**:352–5.
- 42 **Lambrechit W**, Kluth D. Hereditary multiple atresias of the gastrointestinal tract: report of a case and review of the literature. *J Pediatr Surg* 1998;**33**:794–7.
- 43 **Digilio MC**, Marino B, Bagolan P, Giannotti A, Dallapiccola B. Microdeletion 22q11 and oesophageal atresia. *J Med Genet* 1999;**36**:137–9.
- 44 **Kilic SS**, Gurpinar A, Yakut T, Egeli U, Dogruyol H. Esophageal atresia and tracheo-oesophageal fistula in a patient with DiGeorge syndrome. *J Pediatr Surg* 2003;**38**:E21–3.
- 45 **Marsh AJ**, Wellesley D, Burge D, Ashton M, Browne C, Dennis NR, Temple K. Interstitial deletion of chromosome 17 (del(17)(q22q23.3)) confirms a link with oesophageal atresia. *J Med Genet* 2000;**37**:701–4.
- 46 **Harrelson Z**, Kelly RG, Goldin SN, Gibson-Brown JJ, Bollag RJ, Silver LM, Papaioannou VE. Tbx2 is essential for patterning the atrioventricular canal and for morphogenesis of the outflow tract during heart development. *Development* 2004;**131**:5041–52.
- 47 **Sakiyama J**, Yamagishi A, Kuroiwa A. Tbx4-Fgf10 system controls lung bud formation during chicken embryonic development. *Development* 2003;**130**:1225–34.
- 48 **Giorda R**, Cerritello A, Bonaglia MC, Bova S, Lanzi G, Repetti E, Giglio S, Baschiroto C, Pramparo T, Avolio L, Bragheri R, Maraschio P, Zuffardi O. Selective disruption of muscle and brain-specific BPAG1 isoforms in a girl with a 6;15 translocation, cognitive and motor delay, and tracheo-oesophageal atresia. *J Med Genet* 2004;**41**:e71.
- 49 **Clemeniti M**, Di Gianantonio E, Pelo E, Mammi I, Basile RT, Tenconi R. Methimazole embryopathy: delineation of the phenotype. *Am J Med Genet* 1999;**83**:43–6.
- 50 **Ramirez A**, Espinosa de los Monteros A, Parra A, De Leon B. Esophageal atresia and tracheoesophageal fistula in two infants born to hyperthyroid women receiving methimazole (Tapazol) during pregnancy. *Am J Med Genet* 1992;**44**:200–2.
- 51 **Quan L**, Smith DW. The VATER association. Vertebral defects, anal atresia, T-E fistula with esophageal atresia, radial and renal dysplasia: a spectrum of associated defects. *J Pediatr* 1973;**82**:104–7.
- 52 **Kaufman RL**. Birth defects and oral contraceptives. *Lancet* 1973;**1**:1396.
- 53 **Temtamy SA**, Miller JD. Extending the scope of the VATER association: definition of the VATER syndrome. *J Pediatr* 1974;**85**:345–9.
- 54 **Khoury MJ**, Cordero JF, Greenberg F, James LM, Erickson JD. A population study of the VACTERL association: evidence for its etiologic heterogeneity. *Pediatrics* 1983;**71**:815–20.
- 55 **Czeizel A**, Ludanyi I. An aetiological study of the VACTERL-association. *Eur J Pediatr* 1985;**144**:331–7.
- 56 **Rittler M**, Paz JE, Castilla EE. VATERL: an epidemiologic analysis of risk factors. *Am J Med Genet* 1997;**73**:162–9.
- 57 **Boito LD**, Khoury MJ, Mastroiacovo P, Castilla EE, Moore CA, Skjaeravn R, Mutchinick OM, Borman B, Cocchi G, Czeizel AE, Goujard J, Irgens LM, Lancaster PA, Martinez-Frias ML, Merlob P, Ruusinen A, Stoll C, Sumiyoshi Y. The spectrum of congenital anomalies of the VATER association: an international study. *Am J Med Genet* 1997;**71**:8–15.
- 58 **Kallen K**, Mastroiacovo P, Castilla EE, Robert E, Kallen B. VATER non-random association of congenital malformations: study based on data from four malformation registers. *Am J Med Genet* 2001;**101**:26–32.
- 59 **Weaver DD**, Mapstone CL, Yu PL. The VATER association. Analysis of 46 patients. *Am J Dis Child* 1986;**140**:225–9.
- 60 **Nezarati MM**, McLeod DR. VACTERL manifestations in two generations of a family. *Am J Med Genet* 1999;**82**:40–2.
- 61 **Auchterlonie IA**, White MP. Recurrence of the VATER association within a sibship. *Clin Genet* 1982;**21**:122–4.
- 62 **Levrin O**, Atwood C, Henry RT, Milton KL, Neveling K, Rio P, Batish SD, Kall R, Velleuer E, Barral S, Off J, Petrini J, Schindler D, Hanenberg H, Auerbach AD. The BRCA1-interacting helicase BRIP1 is deficient in Fanconi anemia. *Nat Genet* 2005;**37**:931–3.
- 63 **Ryan AK**, Goodship JA, Wilson DJ, Philip N, Levy A, Seidel H, Schuffenhauer S, Oechsler H, Belohradsky B, Prieur M, Aurias A, Raymond FL, Clayton-Smith J, Hatchwell E, McKeown C, Beemer FA, Dallapiccola B, Novelli G, Hurst JA, Ignatius J, Green AJ, Winter RM, Brueton L, Brøndum-Nielsen K, Scambler PJ, et al. Spectrum of clinical features associated with interstitial chromosome 22q11 deletions: a European collaborative study. *J Med Genet* 1997;**34**:798–804.
- 64 **Powell CM**, Michaelis RC. Townes-Brocks syndrome. *J Med Genet* 1999;**36**:89–93.
- 65 **Johnston JJ**, Olivos-Glander I, Killoran C, Elson E, Turner JT, Peters KF, Abbott MH, Aughton DJ, Aylsworth AS, Bamshad MJ, Booth C, Curry CJ, David A, Dinulos MB, Flannery DB, Fox MA, Graham JM, Grange DK, Guttmacher AE, Hannibal MC, Henn W, Hennekam RC, Holmes LB, Hoyne HE, Leppig KA, Lin AE, Macleod P, Manchester DK, Marcellis C, Mazzanti L, McCann E, McDonald MT, Mendelsohn NJ, Moeschler JB, Moghaddam B, Neri G, Newbury-Ecob R, Pagon RA, Phillips JA, Sadler LS, Stoler JM, Tilstra D, Walsh Vockley CM, Zackai EH, Zadeh TM, Brueton L, Black GC, Biesecker LG. Molecular and clinical analyses of Greig cephalopolysyndactyly and Pallister-Hall syndromes: robust phenotype prediction from the type and position of GLI3 mutations. *Am J Hum Genet* 2005;**76**:609–22.
- 66 **Wang H**, Hunter AG, Clifford B, McLaughlin M, Thompson D. VACTERL with hydrocephalus: spontaneous chromosome breakage and rearrangement in a family showing apparent sex-linked recessive inheritance. *Am J Med Genet* 1993;**47**:114–17.
- 67 **Genuardi M**, Chiurazzi P, Capelli A, Neri G. X-linked VACTERL with hydrocephalus: the VACTERL-H syndrome. *Birth Defects Orig Artic Ser* 1993;**29**:235–41.
- 68 **Lomas FE**, Dahlstrom JE, Ford JH. VACTERL with hydrocephalus: family with X-linked VACTERL-H. *Am J Med Genet* 1998;**76**:74–8.
- 69 **Cox PM**, Gibson RA, Morgan N, Brueton LA. VACTERL with hydrocephalus in twins due to Fanconi anemia (FA): mutation in the FAC gene. *Am J Med Genet* 1997;**68**:86–90.
- 70 **Faivre L**, Guardiola P, Lewis C, Dokal I, Ebell W, Zatterale A, Altay C, Poole J, Stones D, Kwee ML, van Weel-Sipman M, Havenga C, Morgan N, de Winter J, Digweed M, Savoia A, Pronk J, de Ravel T, Jansen S, Joenje H, Gluckman E, Mathew CG. Association of complementation group and mutation type with clinical outcome in fanconi anemia. European Fanconi Anemia Research Group. *Blood* 2000;**96**:4064–70.
- 71 **Faivre L**, Portnoi MF, Pals G, Stoppa-Lyonnet D, Le Merrer M, Thauvin-Robinet C, Huet F, Mathew CG, Joenje H, Verloes A, Baumann C. Should chromosome breakage studies be performed in patients with VACTERL association? *Am J Med Genet A* 2005;**137**:55–8.
- 72 **Kahlhase J**, Wischermann A, Reichenbach H, Froster U, Engel W. Mutations in the SALL1 putative transcription factor gene cause Townes-Brocks syndrome. *Nat Genet* 1998;**18**:81–3.
- 73 **Duncan PA**, Shapiro LR. Interrelationships of the hemifacial microsomia-VATER, VATER, and sirenomyelia phenotypes. *Am J Med Genet* 1993;**47**:75–84.
- 74 **Kallen K**, Robert E, Castilla EE, Mastroiacovo P, Kallen B. Relation between oculo-auriculo-vertebral (OAV) dysplasia and three other non-random associations of malformations (VATER, CHARGE, and OEIS). *Am J Med Genet A* 2004;**127**:26–34.
- 75 **Sutphen R**, Galan-Gomez E, Cortada X, Newkirk PN, Kousseff BG. Tracheoesophageal anomalies in oculoauriculovertebral (Goldenhar) spectrum. *Clin Genet* 1995;**48**:66–71.
- 76 **Kelberman D**, Tyson J, Chandler DC, McInerney AM, Slee J, Albert D, Aymat A, Botma M, Calvert M, Goldblatt J, Haan EA, Laing NG, Lim J, Malcolm S, Singer SL, Winter RM, Bitner-Glindzic M. Hemifacial microsomia: progress in understanding the genetic basis of a complex malformation syndrome. *Hum Genet* 2001;**109**:638–45.
- 77 **Basel D**, Goldblatt J. Tibial aplasia—VACTERL association, a new syndrome? *Clin Dysmorphol* 2000;**9**:205–8.
- 78 **Spruijt L**, Devriendt K, Offermans J, Bulstra S, Schrandt-Stumpel C. VATER—tibial aplasia association: report on two patients. *Clin Dysmorphol* 2002;**11**:283–7.
- 79 **Reardon W**, Zhou XP, Eng C. A novel germline mutation of the PTEN gene in a patient with macrocephaly, ventricular dilatation, and features of VATER association. *J Med Genet* 2001;**38**:820–3.
- 80 **Martinez-Frias ML**. Epidemiological analysis of outcomes of pregnancy in diabetic mothers: identification of the most characteristic and most frequent congenital anomalies. *Am J Med Genet* 1994;**51**:108–13.
- 81 **Walsh LE**, Vance GH, Weaver DD. Distal 13q deletion syndrome and the VACTERL association: case report, literature review, and possible implications. *Am J Med Genet* 2001;**98**:137–44.
- 82 **Gershoni-Baruch R**, Zekaria D. Deletion (13)(q22) with multiple congenital anomalies, hydranencephaly and penoscrotal transposition. *Clin Dysmorphol* 1996;**5**:289–94.
- 83 **Benn A**, Warburton D, Byrne JM, Rudelli R, Shonhaut A, Yebova K, Mootabar H, Hsu LY. A fetus with a chromosome 13 ring and placenta with chromosome 13 rod/ring mosaicism. *Prenat Diagn* 1983;**3**:297–302.
- 84 **Goldsmith CL**, Tawagi GF, Carpenter BF, Speevak MD, Hunter AG. Mosaic r(13) in an infant with aprosencephaly. *Am J Med Genet* 1993;**47**:531–3.
- 85 **Guala A**, Dellavecchia C, Mannarino S, Rognone F, Giglio S, Minelli A, Danesino C. Ring chromosome 13 with loss of the region D13S317-D13S285: phenotypic overlap with XK syndrome. *Am J Med Genet* 1997;**72**:319–23.
- 86 **Biles AR Jr**, Luers T, Sperling K. D1 ring chromosome in newborn with peculiar face, polydactyly, imperforate anus, arrhinencephaly, and other malformations. *J Med Genet* 1970;**7**:399–401.
- 87 **Brown S**, Russo J, Chitayat D, Warburton D. The 13q- syndrome: the molecular definition of a critical deletion region in band 13q32. *Am J Hum Genet* 1995;**57**:859–66.

- 88 **Cinti R**, Priolo M, Lerone M, Gimelli G, Seri M, Silengo M, Ravazzolo R. Molecular characterisation of a supernumerary ring chromosome in a patient with VATER association. *J Med Genet* 2001;**38**:E6.
- 89 **McNeal RM**, Skoglund RR, Francke U. Congenital anomalies including the VATER association in a patient with del(6)q deletion. *J Pediatr* 1977;**91**:957-60.
- 90 **Aynaci FM**, Celep F, Karaguzel A, Baki A, Yildiran A. A case of VATER association associated with 9qh+. *Genet Couns* 1996;**7**:321-2.
- 91 **Lubinsky M**. VATER and other associations: historical perspectives and modern interpretations. *Am J Med Genet Suppl* 1986;**2**:9-16.
- 92 **Opitz JM**. Blastogenesis and the "primary field" in human development. *Birth Defects Orig Artic Ser* 1993;**29**:3-37.
- 93 **Martinez-Frias ML**, Frias JL. VACTERL as primary, polytopic developmental field defects. *Am J Med Genet* 1999;**83**:13-16.
- 94 **Chiang C**, Litingtung Y, Lee E, Young KE, Corden JL, Westphal H, Beachy PA. Cyclopia and defective axial patterning in mice lacking Sonic hedgehog gene function. *Nature* 1996;**383**:407-13.
- 95 **Litingtung Y**, Lei L, Westphal H, Chiang C. Sonic hedgehog is essential to foregut development. *Nat Genet* 1998;**20**:58-61.
- 96 **Ramalho-Santos M**, Melton DA, McMahon AP. Hedgehog signals regulate multiple aspects of gastrointestinal development. *Development* 2000;**127**:2763-72.
- 97 **Motoyama J**, Liu J, Mo R, Ding Q, Post M, Hui CC. Essential function of Gli2 and Gli3 in the formation of lung, trachea and oesophagus. *Nat Genet* 1998;**20**:54-7.
- 98 **Mahlapuu M**, Enerback S, Carlsson P. Haploinsufficiency of the forkhead gene Foxf1, a target for sonic hedgehog signaling, causes lung and foregut malformations. *Development* 2001;**128**:2397-406.
- 99 **Boulet AM**, Capechi MR. Targeted disruption of hoxc-4 causes esophageal defects and vertebral transformations. *Dev Biol* 1996;**177**:232-49.
- 100 **Minoo P**, Su G, Drum H, Bringas P, Kimura S. Defects in tracheoesophageal and lung morphogenesis in Nkx2.1(-/-) mouse embryos. *Dev Biol* 1999;**209**:60-71.
- 101 **Mendelsohn C**, Lohnes D, Decimo D, Lufkin T, LeMeur M, Chambon P, Mark M. Function of the retinoic acid receptors (RARs) during development (II). Multiple abnormalities at various stages of organogenesis in RAR double mutants. *Development* 1994;**120**:2749-71.
- 102 **Kim J**, Kim P, Hui CC. The VACTERL association: lessons from the Sonic hedgehog pathway. *Clin Genet* 2001;**59**:306-15.
- 103 **Mo R**, Freer AM, Zinyk DL, Crackower MA, Michaud J, Heng HH, Chik KW, Shi XM, Tsui LC, Cheng SH, Joyner AL, Hui C. Specific and redundant functions of Gli2 and Gli3 zinc finger genes in skeletal patterning and development. *Development* 1997;**124**:113-23.
- 104 **Kimmel SG**, Mo R, Hui CC, Kim PC. New mouse models of congenital anorectal malformations. *J Pediatr Surg*. 2000;**35**: 227-30; discussion 230-1.
- 105 **Raessler E**, Belloni E, Gaudenz K, Jay P, Berta P, Scherer SW, Tsui LC, Muenke M. Mutations in the human Sonic Hedgehog gene cause holoprosencephaly. *Nat Genet* 1996;**14**:357-60.
- 106 **Merei J**, Hasthorpe S, Farmer P, Hutson JM. Visceral anomalies in prenatally adriamycin-exposed rat fetuses: a model for the VATER association. *Pediatr Surg Int* 1999;**15**:11-16.
- 107 **Arsic D**, Cameron V, Ellmers L, Quan QB, Keenan J, Beasley S. Adriamycin disruption of the Shh-Gli pathway is associated with abnormalities of foregut development. *J Pediatr Surg* 2004;**39**:1747-53.
- 108 **Ioannides AS**, Henderson DJ, Spitz L, Capp AJ. Role of Sonic hedgehog in the development of the trachea and oesophagus. *J Pediatr Surg* 2003;**38**:29-36.
- 109 **Spilde TL**, Bhatia AM, Mehta S, Ostlie DJ, Hembree MJ, Preuett BL, Prasad K, Li Z, Snyder CL, Gittes GK. Defective sonic hedgehog signaling in esophageal atresia with tracheoesophageal fistula. *Surgery* 2003;**134**:345-50.
- 110 **Spitz L**, Kiely EM, Morecroft JA, Drake DP. Oesophageal atresia: at-risk groups for the 1990s. *J Pediatr Surg* 1994;**29**:723-5.
- 111 **Dharm P**, Coffey AJ, Abbs S, Vermeesch JR, Dumanski JP, Woodward KJ, Andrews RM, Langford C, Vetrie D. Exon array CGH: detection of copy number changes at the resolution of individual exons in the human genome. *Am J Hum Genet* 2005;**76**:750-62.
- 112 **Visser LE**, de Vries BB, Osoegawa K, Janssen IM, Feuth T, Choy CO, Straatman H, van der Vliet W, Huys EH, van Rijk A, Smeets D, van Ravenswaaij-Arts CM, Knoers NV, van der Burg I, de Jong PJ, Brunner HG, van Kessel AG, Schoenmakers EF, Veltman JA. Array-based comparative genomic hybridization for the genomewide detection of submicroscopic chromosomal abnormalities. *Am J Hum Genet* 2003;**73**:1261-70.
- 113 **Shaw-Smith C**, Redon R, Rickman L, Rio M, Willatt L, Fiegler H, Firth H, Sanlaville D, Winter R, Collea L, Bobrow M, Carter NP. Microarray based comparative genomic hybridisation (array-CGH) detects submicroscopic chromosomal deletions and duplications in patients with learning disability/mental retardation and dysmorphic features. *J Med Genet* 2004;**41**:241-8.
- 114 **Chen Y**, Jurgens K, Hollemann T, Claussen M, Ramadori G, Pieler T. Cell-autonomous and signal-dependent expression of liver and intestine marker genes in pluripotent precursor cells from Xenopus embryos. *Mech Dev* 2003;**120**:277-88.
- 115 **Odum DT**, Zizlsperger N, Gordon DB, Bell GW, Rinaldi NJ, Murray HL, Volkert TL, Schreiber J, Rolfe PA, Gifford DK, Fraenkel E, Bell GI, Young RA. Control of pancreas and liver gene expression by HNF transcription factors. *Science* 2004;**303**:1378-81.