

Review

# Left–right asymmetry in embryonic development: a comprehensive review

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## Abstract

Embryonic morphogenesis occurs along three orthogonal axes. While the patterning of the anterior–posterior and dorsal–ventral axes has been increasingly well characterized, the left–right (LR) axis has only recently begun to be understood at the molecular level. The mechanisms which ensure invariant LR asymmetry of the heart, viscera, and brain represent a thread connecting biomolecular chirality to human cognition, along the way involving fundamental aspects of cell biology, biophysics, and evolutionary biology. An understanding of LR asymmetry is important not only for basic science, but also for the biomedicine of a wide range of birth defects and human genetic syndromes. This review summarizes the current knowledge regarding LR patterning in a number of vertebrate and invertebrate species, discusses several poorly understood but important phenomena, and highlights some important open questions about the evolutionary origin and conservation of mechanisms underlying embryonic asymmetry.

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## 1. Introduction

The geometrical invariance known as symmetry is a prominent aspect of developmental morphology during embryogenesis. Animal body-plans occur in a wide variety of symmetries: spherical (e.g. volvox), radial (e.g. sea anemone), chiral (e.g. snails, ciliates), bilateral (e.g. planaria) and pseudo-bilateral (e.g. man). Vertebrates have a generally bilaterally symmetrical body-plan, but this symmetry is broken by the consistently asymmetric placement of various internal organs such as the heart, liver, spleen, and gut, or the asymmetric development of paired organs (such as brain hemispheres and lungs). Symmetries are repeatedly broken during development. For example, the radial symmetry of the early chick blastoderm is broken into a bilateral symmetry by the appearance of Köhler's sickle and then the primitive streak. This is further broken into a definitive pseudo-symmetry by

the right-sided looping of the heart tube. A fascinating atlas of morphological asymmetries throughout the animal kingdom is given in Neville (1976).

Developmental noise often results in pseudo-random characteristics and minor stochastic deviations known as fluctuating asymmetry; however, the most interesting phenomenon is invariant (i.e. consistently biased among all normal individuals of a given type) differences between the left and right sides. For reasons of space as well as because these are likely to be secondary to embryonic asymmetries, this review largely neglects behavioral/sensory asymmetries (such as lobster claw morphology which is determined by neurological activity). A huge literature on brain lateralization phenomena in human beings exists as well (Harnad, 1977), but many of these asymmetries are secondary and arise as a result of cultural environmental biasing factors.

The establishment of left–right (LR) asymmetry raises a number of fascinating biological questions. Why does asymmetry exist at all? What are the implications of asymmetry for the normal structure and physiology of the heart, gut, and brain? Why are all normal individuals not only

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asymmetric, but asymmetric to the same direction (i.e. why a consistent bias and not a 50/50% racemic population, given that individuals with full inversion are not phenotypically impaired)? When, during evolution, did *handed* asymmetry appear, and were there true bilaterally symmetrical organisms prior to the invention of oriented asymmetry (Cooke, 2004)? Is it connected to chirality in lower forms (such as snail shell coiling and chirality in some plants)? At what developmental stages is asymmetry initiated in vertebrate embryos? How conserved are the molecular mechanisms establishing correct asymmetry in animals with drastically different modes of gastrulation? And, how can the LR axis be consistently oriented with respect to the anterior–posterior (AP) and dorso-ventral (DV) axes in the absence of any macroscopic feature of chemistry or physics which distinguishes left from right? Answers to these questions require a detailed understanding, at the molecular, genetic, and biochemical levels, of the formation of biased asymmetry in embryos.

The LR axis itself follows automatically from the definition of the AP and DV axes, as it is perpendicular to both; however, consistently imposed asymmetry across it is fundamentally different from patterning along the other two axes. Firstly, while the AP and DV axes can be set by exogenous cues such as gravity, or sperm entry point, there is no independent way to pick out the left (or right) direction, since no known macroscopic aspect of nature differentiates left from right. One possible way to use a fundamental force to orient the LR axis relative to the other two axes was suggested by Huxley and deBeer (1963). They proposed that LR asymmetry was oriented during embryonic development by an electric current running down the length of

the notochord, which would generate a magnetic field vector pointing R or L, if measured at the dorsal or ventral sides. Although a correlation between the Earth's geomagnetic field reversals and shell chirality has been observed (Harrison and Funnel, 1964), the nature of a causal relationship (if any) is unknown, and there is no evidence to date of a magnetic field being utilized during LR patterning in any species.

While in most species all normal individuals are asymmetrical in the same direction, animals with complete mirror reversal of internal organs can arise (*situs inversus totalis*) and are otherwise phenotypically unimpaired. Thus, while it is possible to devise plausible evolutionary reasons for why organisms might be asymmetric in the first place (optimal packing, fluid dynamics, maximizing surface area of tubes, etc. (Kilner et al., 2000)), there is no obvious reason for why they should all be asymmetric to the same direction. It is, after all, much easier to imagine a developmental mechanism for generating antisymmetry (such as local amplification and long-range inhibition of stochastic biochemical differences resulting in a morphologically racemic population), than for biasing the LR axis to a given direction. It is possible that tight concordance (which is advantageous) requires specific bias, but no data yet indicate why these two logically distinct processes must be linked.

## 2. Pre-molecular data

Prior to the first molecular studies of the LR axis, glimpses into mechanisms of asymmetry were provided by a variety of drugs which cause defects in a LR-asymmetric manner or randomize asymmetry (Table 1). These form

Table 1  
Drugs which have LR-relevant phenotypes

Drug	Function	Species	Result	Reference
A23187	Ca <sup>++</sup> ionophore	Xenopus	Heterotaxia	Toyoizumi et al. (1997)
Cadmium	Heavy metal	Xenopus	Gut malrotations	Sunderman et al. (1991, 1992)
Cadmium	Heavy metal	Rat	Left limb deformities	Barr (1973)
Cadmium	Heavy metal	Mouse	Right limb deformities	Layton and Layton (1979)
Acetazolamide	Carbonic anhydrase inhibitor	Rat	Right limb deformities	Layton and Hallesy (1965)
MNNG	Alkylating agent	Mouse	Left ectodactyly	Inouye and Murakami (1978)
Acetoxymethyl-methylnitrosamine	Alkylating agent	Mouse	Left limb deformities	Bochert et al. (1985)
Xyloside	Proteoglycan synthesis inhibitor	Frog	No cardiac looping	Yost (1990b)
Nitrous oxide	Anesthetic	Rat	Heterotaxia	Fujinaga et al. (1990)
Retinoic acid	Teratogen	Hamster	Heterotaxia	Shenefelt (1972)
Phenylephrine	Adrenergic agonist	Rat	Heterotaxia	Fujinaga and Baden (1991)
Methoxamine	Adrenergic agonist	Rat	Heterotaxia	McCarthy (1990)
Staurosporine	PKC inhibitor	Rat	Heterotaxia	Fujinaga and Baden (1993a)
Lidocaine	Anesthetic	Rat	Heterotaxia	Fujinaga and Baden (1993b)
Nitrofurazone	Antibiotic	Rat	Right-sided hypoplasia	Greenaway et al. (1986)
RGD polypeptides	Block ECM interactions	Frog	Heterotaxia	Yost (1992)

a diverse group of compounds, which includes even such simple substances as cadmium. The developmental pharmacology of these drugs has not yet been explored to characterize endogenous targets involved in LR patterning, with the important exceptions that an adrenergic pathway is known to be involved (Fujinaga and Baden, 1991), and that PKC is known to participate in asymmetry in *Xenopus* (Kramer et al., 2002).

Of particular interest are the effects that present in a unilateral manner; no tractable genetic models of this phenomenon have yet been described. The drugs which cause more extensive limb defects on one side were suggested (Milairé, 1985) to be due to a differential blood supply to the two limbs (due to asymmetry in blood vessels exiting the heart). This is made somewhat unlikely by the fact that cadmium causes opposite-sided defects in rats and mice (Barr, 1973; Layton and Layton, 1979), while cardiac anatomy and relative vessel size of both species are quite similar. Such observations hint that subtle molecular differences may exist between organs which are assumed to be symmetrical (such as left and right limbs, eyes, etc.), establishing a true LR axis rather than a medio-lateral one (although the data do not require graded positional information along this LR axis, but merely L vs. R identity). This counter-intuitive and as yet unexplored idea is also suggested by several human syndromes. Holt-Oram syndrome (Tbx5-related) presents upper limb malformations which are much more common on the left side (Bruneau et al., 1999; Hatcher et al., 2000; Newbury-Ecob et al., 1996; Smith et al., 1979), while fibular a/hypoplasia affects the right side more often (Lewin and Opitz, 1986). Indeed, a variety of human syndromes affecting paired organs have a significant bias for one side (Paulozzi and Lary, 1999). Moreover, genetic conditions exist in which a large number of tissues, all on one side of the body, resume growth in adulthood (Clericuzio, 1993; Fraumeni et al., 1967; Kloepffel et al., 2002; Leung et al., 2002; Sarkar et al., 1992; Stalens et al., 1993), suggesting that a wide range of tissues within morphologically symmetrical organs may not only possess positional information with respect to the LR axis but may maintain this identity for decades after completion of embryogenesis. Molecular insight into this phenomenon is likely to open important advances in developmental patterning.

### 3. Left–right asymmetry meets molecular biology

While mechanisms underlying antero-posterior and DV asymmetry have been studied in detail with the advent of molecular genetics, the mechanistic basis for LR asymmetry was obscure until the last 10–15 years (Burdine and Schier, 2000; Levin and Mercola, 1998a; Mercola, 2003; Mercola and Levin, 2001; Yost, 2001). Tables 2–4 summarize the endogenous developmental molecules players in the LR

pathway, and show available conservation data among various model systems. These gene products have been identified in forward- and reverse-genetics approaches (exemplified by the zebrafish mutants and genes like *Sonic hedgehog*, respectively), and almost all have roles in embryonic processes other than LR asymmetry. Some are asymmetrically expressed at the level of mRNA or protein, while others exhibit no asymmetry. A number of mechanisms have been identified with molecular markers but the details of their function remain poorly understood. One example is the necessity for apoptosis in the midline of the chick embryo for normal LR asymmetry (Kelly et al., 2002); FGF8 and Brachyury are markers for midline cells fated to die, but it is not yet known in detail what endogenous mechanisms underlie the specification of the apoptotic cells, nor how their death provides instructive signals to downstream LR pathways.

Conceptually, LR patterning is divided into three phases (Levin and Mercola, 1998a); the flow of information is schematized in Fig. 1. In the final phase, individual organs utilize cell migration, differential proliferation, cytoskeletal organization, and other mechanisms to achieve asymmetries in their location or morphogenesis (Horne-Badovinac et al., 2003; Manasek, 1981; Stalsberg, 1969a,b). Consistent with their downstream position, and counter to earlier proposals (Waddington, 1937), a number of recent studies have shown that the individual organs' literalities are set, and can be experimentally randomized, independently (Chin et al., 2000a; Levin et al., 1997b). Biophysical mechanisms used to shape organogenesis include the extracellular matrix (Tsuda et al., 1996; Yue et al., 2004) and actin bundles (Itasaki et al., 1989, 1991) in the chick heart tube, and differential rates of elongation in the frog gut tube (Muller et al., 2003). Genetic control over these pathways is mediated proximately (if not directly) by genes such as *flectin*, the bHLH family members *EHAND* and *DHAND*, and the transcription factor *Tbx5* (Angelo et al., 2000; Bruneau et al., 1999; Fernandez-Teran et al., 2000; Hatcher et al., 2000; Sparrow et al., 1998; Srivastava, 1995; Takeuchi et al., 2003; Tsuda et al., 1996). The mechanisms underlying embryonic turning remain poorly understood (Constam and Robertson, 2000). The topological deformations undergone by asymmetric tissues are more complex than usually assumed (Manner, 2004), and complete understanding is likely to require mathematical or physical models in addition to molecular biology.

Upstream of these processes lies a pathway of asymmetric genes which are expressed in cell fields only on one side of the embryo's midline. By inducing or repressing transcription of downstream asymmetric targets, they propagate signals among sub-populations of cells (such as node and lateral plate mesoderm), which eventually dictate sidedness for the organs undergoing asymmetric morphogenesis. These cascades of asymmetric gene expression form the middle phase of LR

Table 2

Asymmetrically expressed genes in embryos which have been the focus of a paper on LR asymmetry

Gene	Species	Product/role	Side	Reference
Lefty	Mouse, chick, frog	TGF- $\beta$ -family signaling molecule	Left	Branford et al. (2000), Cheng et al. (2000b), Essner et al. (2000), Meno et al. (1996, 1998)
Lrd	Mouse	Dynein	Either	Supp et al. (1997, 1999)
Activin- $\beta$ B	Chick	TGF- $\beta$ -family signaling molecule	Right	Levin et al. (1997a)
cAct-RIIa	Chick	Activin receptor	Right	Levin et al. (1995)
Shh	Chick	Signaling molecule	Left	Levin (1995)
CSnR	Chick	Zinc finger protein	Right	Isaac et al. (1997)
Nodal	Chick, mouse, frog	TGF- $\beta$ -family signaling molecule	Left	Collignon et al. (1996), Levin et al. (1995), Lohr et al. (1997a), Lowe et al. (1996a), Morokuma et al. (2002)
CPTC	Chick	Shh Receptor	Left	Levin (1998b), Pagan-Westphal and Tabin (1998)
Cerberus	Chick	Signaling molecule	Left	Zhu et al. (1999)
BMP-4	Zebrafish, chick	BMP family signaling molecule	Left	Chen et al. (1997), Monsoro-Burq and LeDouarin (2000)
Pitx-2	Chick, frog, mouse	Transcription factor	Left	Logan et al. (1998), Morokuma et al. (2002), Ryan et al. (1998)
NKX3.2	Chick, mouse	Transcription factor	Left in chick, right in mice	Schneider et al. (1999)
Follistatin	Chick	Signaling molecule	Right	Levin (1998a)
FGF-8	Chick	Growth factor	Right	Boettger et al. (1999)
Flectin <sup>a</sup>	Chick	Extra-cellular matrix molecule	Left	Tsuda et al. (1996)
DHAND	Chick, mouse, frog	bHLH transcription factor	Right	Angelo et al. (2000), Srivastava (1995)
EHAND	Chick, mouse, frog	bHLH transcription factor	Left	Angelo et al. (2000), Biben and Harvey (1997), Cserjesi et al. (1995), Sparrow et al. (1998), Srivastava (1995)
Caronte	Chick	Cerberus/DAN family member	Left	Yokouchi et al. (1999)
N-Cadherin	Chick	Adhesion molecule	Right node, left groove	Garcia-Castro et al. (2000)
Cx43	Chick	Gap junction protein	Right	Levin and Mercola (1999)
Islet-1	Chick	LIM homeobox gene	Left	Yuan and Schoenwolf (2000)
H <sup>+</sup> /K <sup>+</sup> -ATPase	Frog, chick	H <sup>+</sup> and K <sup>+</sup> ion pump	Right	Levin et al. (2002)
PKI- $\alpha$	Chick	PKA inhibitor	Right	Kawakami and Nakanishi (2001), Rodriguez-Esteban et al. (2001)
NCX-1	Chick, mouse	Sodium-calcium exchanger	Right	Linask et al. (2001)
HoxC-8	Frog	Transcription factor	Left	Thickett and Morgan (2002)
Xin	Mouse	?	Right	Wang et al. (1999)
Southpaw	Zebrafish	TGF- $\beta$ family	Left	Long et al. (2003)
Mid1	Chick	Microtubule-associated protein	Right	Granata and Quaderi (2003)
Isy-6	<i>C. elegans</i>	Micro RNA repressor	Left	Johnston and Hobert (2003)
Dll1	Chick	Delta-like signaling molecule	Left	Raya et al. (2004)
14-3-3E	Frog	14-3-3 family	Right	Bunney et al. (2003)
Kif5C	Chick	Kinesin motor	Right	Dathe et al. (2004)
Cyclops	Zebrafish	Nodal-related	Left	Concha et al. (2000)
Leftover	Zebrafish	?	Left	Concha et al. (2000), Gamse et al. (2003)
Pcl-2	Chick	Transcription repressor	Right	Wang et al. (2004)
HB-EGF	Mouse	Growth factor	Left	Golding et al. (2004a,b)

<sup>a</sup> Antibody epitopes.

patterning. However, for whichever asymmetric gene is at the top of the pathway, it is necessary to ask what determined its asymmetry. Thus, in the first phase of LR patterning, an as-yet unknown mechanism must orient

the LR axis with respect to the other two axes. While theoretical candidate mechanisms have been proposed (Brown and Wolpert, 1990), no mechanism has been conclusively shown to initiate asymmetry.

Table 3  
Asymmetrically expressed genes which have not been the focus of a LR paper

Gene	Species	Product/role	Side	Reference
HNF3- $\beta$	Chick, mouse	Winged-helix transcription factor	Left	Collignon et al. (1996), Levin et al. (1995)
CWnt-8C	Chick	wnt-family signaling molecule	Right	Levin (1998c), Pagan-Westphal and Tabin (1998)
hLAMP-1 <sup>a</sup>	Chick	Extra-cellular matrix molecule	Left	Smith et al. (1997)
JB3 <sup>a</sup>	Chick	Extra-cellular matrix molecule	Right	Smith et al. (1997), Wunsch et al. (1994)
HGF	Chick	Kringle signaling molecule	Left	Streit et al. (1995)
Hrlim	Ascidian	LIM-family signaling molecule	Right	Wada et al. (1995)
Rtk2	Zebrafish	Eph receptor	Right	Schilling et al. (1999)
Fli-1	Zebrafish	Transcription factor	Left	Schilling et al. (1999)
DM-GRASP	Zebrafish	Adhesion protein		Schilling et al. (1999)
Xbap	Frog	Transcription factor	Left	Newman et al. (1997)
Hest1	Zebrafish	ASIC ion channel	Left	Concha et al. (2003)

<sup>a</sup> Antibody epitopes.

The developmental timing of each phase differs among species, though asymmetric gene expression almost always begins at or shortly after gastrulation. The LR axis is probably specified after the AP and DV axes, and is determined with respect to them (Danos and Yost, 1995a; McCain and McClay, 1994). The timing of the initiation of LR asymmetry in the various species is particularly controversial, but the mechanisms underlying different

aspects of LR patterning in various species are beginning to be uncovered in significant detail.

#### 4. Invertebrates

While the genetics of symmetry determination have been addressed in plants (Endress, 1999, 2001; Theissen,

Table 4  
Genes involved in LR patterning which are not asymmetrically expressed

Gene	Species	Product/role	Reference
Iv	Mouse	Dynein (cytoplasmic transport or ciliary motor)	Lowe et al. (1996b), Supp et al. (1997, 1999, 2000)
Inv	Mouse	?	Mochizuki et al. (1998), Morgan et al. (1998, 2002)
Connexins	Frog, chick, man	System of gap-junctional cell-cell signaling	Britz-Cunningham et al. (1995), Levin and Mercola (1998c, 1999)
No turning	Mouse	Midline patterning	Melloy et al. (1998)
SIL	Mouse	Midline patterning	Izraeli et al. (1999)
KIF-3	Mouse	Component of ciliary motor	Nonaka et al. (1998), Takeda et al. (1999a)
Polaris	Mouse	?	Murcia et al. (2000)
HFH-4	Mouse	Transcription factor	Brody et al. (2000), Chen et al. (1998)
Lin-12	<i>C. elegans</i>	Notch signaling molecule	Hermann et al. (2000)
Delta-1	Mouse	Notch signaling molecule	Przemeck et al. (2003)
Notch	Mouse, zebrafish	Notch signaling molecule	Krebs et al. (2003), Raya et al. (2003a)
Smo	Mouse	Membrane protein involved in hedgehog signaling	Zhang et al. (2001)
Ihh	Mouse	Member of hedgehog signaling proteins	Zhang et al. (2001)
GDF-1/Vg-1	Mouse, frog	TGF- $\beta$ -family signaling molecule	Hyatt et al. (1996), Hyatt and Yost (1998), Rankin et al. (2000), Wall et al. (2000)
DNAH5	Human	Dynein	Ibanez-Tallon et al. (2002), Olbrich et al. (2002)
PCKD-2	Mouse	Polycystin-2 ion channel	Pennekamp et al. (2002)
ZIC3	Human, mouse, frog	Zinc-finger protein	Gebbia et al. (1997), Kitaguchi et al. (2000), Purandare et al. (2002)
EGF-CFC	Mice, Zebrafish	Extracellular receptor	Yan et al. (1999a)
Furin	Mice	Proprotein convertase	Constam and Robertson (2000), Roebroek et al. (1998)
Brachyury	Mice	Transcription factor	King et al. (1998)
Ednrb	Mice	Piebald deletion complex	Welsh and O'Brien (2000)
Rotatin	Mice	Transmembrane protein	Faisst et al. (2002)
PDI-P5	Zebrafish	Protein disulfide isomerase	Hoshijima et al. (2002)
Pol- $\lambda$	Mouse	DNA polymerase	Kobayashi et al. (2002)
PA26	Human	Sestrin-family	Peeters et al. (2003)
Cryptic	Mouse, human, zebrafish	EGF-CFC gene	Bamford et al. (2000), Gaio et al. (1999b), Yan et al. (1999b)
Charon	Zebrafish	Cerberus-family protein	Hashimoto et al. (2004)



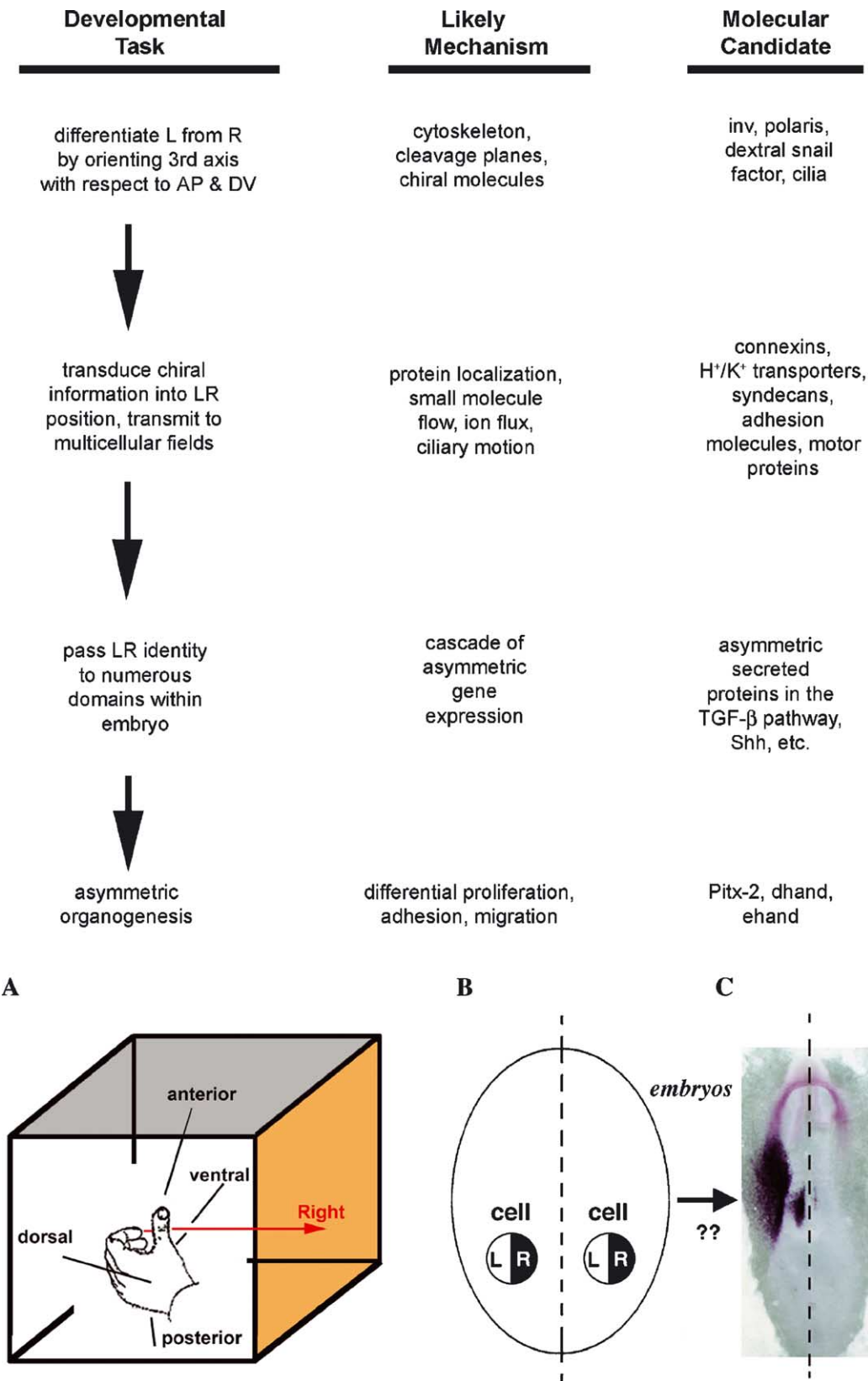


Fig. 1. The progressive flow of LR information is shown as a function of time, from its orientation with respect to the LR axis (A), to its conversion to positional information with respect to the midline and its imposition upon large-scale cell fields (B,C). Candidate mechanisms for each step are shown.

2000), and chiral forms exist among the protozoa (Frankel, 1991; Nelsen et al., 1989), true LR asymmetry appears to be mainly a feature of the animal kingdom. The organs possessing asymmetries, as well as the direction of their asymmetry, are evolutionarily well conserved. The heart is asymmetrically located in the mollusks (McMurrich, 1894); the *situs* of the stomach and the liver (Romer, 1962) is the same among fish, reptiles, birds, and mammals. In sea urchins, the asymmetric position of the adult rudiment in the larva has been studied (Aihara and Amemiya, 2000, 2001; McCain and McClay, 1994).

Several kinds of molluscs undergo spiral cleavage and secrete an exoskeleton shaped like a conical spiral. In 3D space, such spirals can have two possible variants: a left-handed and a right-handed helix (which are otherwise identical). Each particular species of snail has invariant (consistent) chirality, but there are species which utilize each type of coiling. Murray and Clarke (1966) found that the direction of coiling of *Plionoma suturalis* is maternally inherited and sinistrality is dominant to dextrality. Freeman and Lundelius (1982), studying a different species, found that dextrality is dominant; the dextral gene apparently functions via an as yet unidentified cytoplasmic component.

Amphioxus, considered to be the ancestor of vertebrates, exhibits many LR asymmetries (Jefferies et al., 1996); one of the most striking occurs in somitogenesis (Minguillon and Garcia-Fernandez, 2002). Some of the genes known to be asymmetrically expressed in vertebrates are beginning to be cloned in amphioxus, and information on the conservation of lateralized expression should become available soon (Araki et al., 1996; Boorman and Shimeld, 2002a,b; Minguillon and Garcia-Fernandez, 2002; Shimeld, 1999; Terazawa and Satoh, 1995, 1997). The Ascidian *Nodal*- and *Pitx*-related genes exhibit the well-conserved left-sided expression (Morokuma et al., 2002).

In contrast to its pivotal contributions to other aspects of developmental biology, *Drosophila* has not played a key role in uncovering mechanisms of LR asymmetry. For example, selection for LR asymmetries in *Drosophila*, in hopes of generating a genetically tractable mutant, has not been successful (Tuinstra et al., 1990). However, it is now known from mutant analysis that *Drosophila* possesses genes which govern the helical torsion of the body (Martin-Blanco and Garcia-Bellido, 1996) and the rotation of the embryonic gut proventriculus (Adam et al., 2003; Hayashi and Murakami, 2001; Ligoxygakis et al., 2001). Both of these asymmetries are instances of chirality, which appears to dominate in the invertebrates (ciliates, mollusks, etc.). However, recent morphometric analysis has revealed a subtle but real directed asymmetry in wing size (Klingenberg et al., 1998), suggesting that novel mechanisms orienting the LR axis in fruit flies remain to be discovered.

In *Caenorhabditis elegans*, the embryonic cell lineage is asymmetrical: although the animal exhibits few LR asymmetries, many of its contralaterally analogous cells arise via different lineages on the two sides of the embryo (Wood and Kershaw, 1991). Larvae and adults also exhibit invariant LR asymmetries in the nervous system and gut. It is now known that induction at the 12-cell stage by the MS blastomere is necessary to establish the differences between left and right pairs of blastomeres in the anterior part of the embryo (Hutter and Schnabel, 1995). The microRNA *lsy-6* controls the neuronal left/right asymmetry of chemosensory receptor expression (Johnston and Hobert, 2003). Two lateral blast cells P(11/12)L and P(11/12)R are symmetric at hatching, but migrate subsequently in opposite AP directions during the first larval stage and adopt different fates; this is downstream of the Notch pathway (Delattre and Felix, 2001; Hermann et al., 2000), as are the consistent cell movements leading to a twist of the intestinal primordium. Interestingly, a gene related to the *C. elegans* cell polarity determination pathway (*Par* family) has now been shown to be involved in the LR pathway in *Xenopus* (Bunney et al., 2003), suggesting possible conservation of basic vertebrate and invertebrate asymmetry-generating molecules.

The relationship and evolutionary origin of asymmetry-generating mechanisms in vertebrates and invertebrates is currently a very controversial issue (Boorman and Shimeld, 2002a; Jefferies, 1991). In both amphioxus and ascidians, expression of the homeobox transcription factor *Pitx2* is left-sided, suggesting that LR asymmetry in all chordates is regulated by a conserved developmental pathway which evolved before the separation of the lineages leading to living chordates. Other molecules such as *Notch* are involved in asymmetry in both vertebrates and invertebrates, but the molecular details of their action are distinct (Delattre and Felix, 2001; Hermann et al., 2000; Krebs et al., 2003; Przemek et al., 2003; Raya et al., 2003a,b, 2004; Vincent, 2003).

## 5. Fish

Flatfishes acquire a profound asymmetry in eye location (and scale/skin pigmentation) during metamorphosis from bilaterally symmetric larvae (Hashimoto et al., 2002; Matsumoto and Seikai, 1992; Okada et al., 2001a,b). Analysis of mutants in the zebrafish embryo has identified a number of genes involved in LR patterning (Yost, 1998), though some of these are likely to represent secondary LR effects of disrupted notochord or AP/DV patterning (see discussion of midline barrier below). In zebrafish, asymmetric markers such as *Lefty*, *Nodal*, and *Pitx2* exhibit well-conserved asymmetric expression during neurulation and somitogenesis (Cheng et al., 2000b; Essner et al., 2000; Liang et al., 2000).

Very little is known about early LR patterning steps in the zebrafish and it remains to be determined whether mechanisms implicated upstream of asymmetric gene expression (discussed below) function in fish, and whether the initial steps of asymmetry occur prior to or after the start of gastrulation. Rhythmic  $\text{Ca}^{++}$  waves have been described during fish gastrulation (Gilland et al., 1999), consistent with the calcium fluxes discovered (McGrath et al., 2003; Raya et al., 2004) in mice and chicks (see below), although the connection to downstream LR markers is not understood. However, the zebrafish has enabled some unique insight into neurological asymmetry.

The dorsal diencephalon of zebrafish embryos is LR asymmetric. The pineal complex consists of the pineal organ anlage and a left-sided parapineal. The neighboring brain nuclei (L and R dorsal habenulae) show consistent differences in size, density of neuropil, and gene expression. Zebrafish mutants have demonstrated a correlation between LR position of parapineal and the laterality of habenular nuclei; these asymmetries are downstream of Nodal signaling, illustrating the link between brain and visceral asymmetry. Selective ablation of the parapineal organ results in the loss of habenular asymmetry (Gamse et al., 2003; Halpern et al., 2003). One of the recent asymmetric genes expressed in zebrafish habenulae is *hest1* (Concha et al., 2003), which is a pH-sensitive ion channel. In light of the involvement of  $\text{H}^+$  flux in early LR asymmetry in frog and chick embryos (see below), it will be interesting to find out whether  $\text{H}^+$  flux is also involved in much later generation of brain asymmetry. Importantly, it has been shown that one of the downstream endpoints of the early brain asymmetry is behavioral. Most species of fish examined preferentially utilize the right eye when attacking rivals (Bisazza and de Santi, 2003; Miklosi and Andrew, 1999).

## 6. Amphibia

Experiments in *Xenopus* first suggested that the LR axis might be established extremely early, and to be intimately linked with DV axis formation (Yost, 1991). The DV axis is initiated by sperm entry during fertilization, followed by a cytoplasmic rotation during the first cell cycle, driven by a microtubule array at the vegetal cortex (Gerhart et al., 1989). Work from the Yost lab showed that embryos in which the microtubule array was blocked, but which were tilted manually to rescue the DV and AP axes exhibited laterality defects, suggesting that the LR axis may be dependent on the transient microtubule array during the first cell cycle. The appearance of LR asymmetry between fertilization and the first cell division is consistent with the recent work showing asymmetric mRNA and protein localization during early the first few cleavages (Bunney et al., 2003; Levin et al., 2002). While the mechanisms which process LR information during

gastrulation in amphibia are largely unknown, the *Xenopus* embryo has allowed discovery of a number of mechanisms which underlie asymmetry at the earliest stages known in any species.

The *Xenopus* system was the first to allow ‘molecular’ studies of LR asymmetry in embryogenesis (Yost, 1990a, 1992). Localized perturbation of a small patch of extracellular matrix by microsurgery, as well as global perturbation of the extracellular matrix by microinjection of Arg-Gly-Asp peptides or heparinase into the blastocoel, resulted in randomization of LR asymmetry. This work provided the first molecular entrypoint into LR asymmetry, and suggested that the extracellular matrix participated in transfer of LR information in development. Inhibition of proteoglycan synthesis with the drug  $\beta$ -xyloside prevents heart looping in *Xenopus* (Yost, 1990b). The effect occurred well before heart looping, was cell-autonomous, and was proposed to involve migratory cells of the cardiac primordia.

Based on the proposal that heparan sulfate proteoglycans (HSPGs) or the ECM on the basal surface of the ectoderm transmits LR information to mesodermal primordia during gastrulation (Yost, 1992), Teel and Yost examined the roles of the Syndecan family; syndecan-1 and -2 are maternally expressed HSPGs specifically located in the animal cap ectoderm (Teel and Yost, 1996). Using dominant-negative and loss-of-function approaches, it was shown that syndecan-2 is involved in LR asymmetry (Kramer and Yost, 2002) in *Xenopus*. A cytoplasmic domain of Syndecan-2 is phosphorylated in cells on the right but not left half of the frog embryo during gastrulation. Moreover, they showed that attachment of multiple heparan sulfate glycosaminoglycans on syndecan-2 and functional interaction of these sites with the cytoplasmic domain are an obligate part of LR patterning during gastrulation, immediately prior to the migration of mesoderm across ectoderm. Kramer and Yost also presented biochemical data on the direct interaction of Syndecan-2 with Vg1 (a candidate for the LR coordinator (Hyatt and Yost, 1998)), suggesting that these two molecules function together during LR patterning at gastrulation.

Another key finding in *Xenopus* was the discovery of an experimental perturbation which can produce almost full *situs inversus*; this is especially interesting since almost every other reported manipulation results in heterotaxia—an independent randomization of *situs* and not full reversal (or loss of asymmetry). The active form of Vg1, a TGF $\beta$  family member, can almost completely invert the LR axis when misexpressed on the right side (R3 blastomere) of a *Xenopus* embryo (Hyatt et al., 1996; Hyatt and Yost, 1998). This suggests that Vg1 normally acts in descendants of the L3 blastomere, which contribute to the left LPM, and the model suggests signaling through ALK2 and mutual antagonism with BMP on the right side of the embryo (Ramsdell and Yost, 1999). Axial inversion is specific to the activated Vg1 and cannot be mimicked by Activin. While these data are



consistent with an early LR pattern in the pre-gastrula stage *Xenopus* embryo, the precise timing remains uncertain since the persistence of the injected mRNA to later stages raises the possibility that the injected Vg1 persists in the embryo and mimics a later signal. Endogenous Vg1 protein in early *Xenopus* embryos (and especially, asymmetries therein) have yet to be characterized. Along-side the above-mentioned secreted signaling molecules, *Xenopus* embryos have also allowed the discovery of LR mechanisms which depend on a different channel for cellular communication: gap junctions.

Gap junctions are channels connecting adjacent cells that allow the direct transfer of small molecule signals. The cell biology of gap junctions has been described in several excellent recent reviews (Falk, 2000; Goodenough et al., 1996), and gap junctional flow is involved in a number of important patterning events in embryonic development and tumor progression (Guthrie and Gilula, 1989; Levin, 2001; Lo, 1996). Based on a (now controversial) report that several unrelated patients with viscerio-atrial heterotaxia contain potential mutations within Connexin43 (Britz-Cunningham et al., 1995), and data which indicated asymmetric patterns of GJC (Guthrie, 1984; Guthrie et al., 1988) in early frog blastomeres, Levin and Mercola tested the hypothesis that gap junctional paths were a mechanism by which LR information was communicated across large cell fields (Levin and Mercola, 1998c). *Xenopus* embryos at early cleavage stages were shown to contain a junctional path across the dorsal blastomeres, and a zone of junctional isolation on the ventral midline, confirming with a double-dye system previous observation using a single small-molecule probe (Brizuela et al., 2001; Guthrie, 1984; Olson et al., 1991, but see Landesman et al., 2000). Injection of mRNA encoding a dominant negative connexin protein into dorsal blastomeres or wild-type connexins into ventral blastomeres both resulted in heterotaxia and randomization of XNR-1 expression in the absence of other developmental defects (Levin and Mercola, 1998c).

These results indicate that an endogenous path of GJC between dorsal and lateral blastomeres, as well as the isolation across the ventral midline, are necessary for normal LR asymmetry in *Xenopus*. Pharmacological blocker experiments suggested that the gap-junctional system begins to function in LR asymmetry during cleavage stages, and is upstream of asymmetric *XNR-1* and heart tube looping. It was proposed (Levin and Mercola, 1998c; Levin and Nascone, 1997) that small molecule determinants are initially randomly distributed, but traverse the circumferential GJC path unidirectionally, accumulating on one side of the midline, and then induce asymmetric gene expression. Similar data were later obtained in the chick embryo (see below). The identities of the putative low molecular weight determinants remain unknown (although pre-nervous neurotransmitters are now a plausible candidate (Fukumoto et al., 2003)).

One of the key aspects of the GJC model is that the junctional flow must be net unidirectional, in order to derive

a LR asymmetry from the existing dorsoventral difference in GJC (although no individual signaling molecule needs to traverse the entire path). In some contexts, chemically rectifying or 1-way junctions have been observed (Flagg-Newton and Loewenstein, 1980; Robinson et al., 1993; Xin and Bloomfield, 1997; Zahs and Newman, 1997; Zahs, 1998), and it is tempting to visualize unidirectional paths of heterotypic gap junctions arranged appropriately to provide a ratchet mechanism for accumulation of LR morphogen on one side of the midline. However, because thermodynamics forbids the generation of a gradient without an expenditure of energy, GJC models require an energetic process to drive the chiral (net unidirectional) distribution of the small molecules through the circumferential path. A model in which a voltage difference provides an electrophoretic force pushing charged molecules in preferred directions through GJC paths suggested the hypothesis that ion fluxes may be an obligatory aspect of early LR patterning in *Xenopus*.

A pharmacological screen of hundreds of various types of ion channels, pumps, and co-transporters (Levin et al., 2002) specifically implicated four target genes involved in  $H^+$  and  $K^+$  flux (Adams and Levin, 2003; Chen and Levin, 2004). One of these, the  $H^+/K^+$ -ATPase, functions during early cleavage stages. Moreover, maternal  $H^+/K^+$ -ATPase mRNA is asymmetrically localized during the first two cell divisions, demonstrating that asymmetry is generated by two hours post-fertilization. Examination of the *situs* of asymmetric genes (*xNR-1*, *xLefty*, and *xPitx-2*) following early exposure to blockers of the  $H^+/K^+$ -ATPase revealed that, consistently with the early asymmetrical expression, the ion flux mechanism is upstream of the asymmetric expression of those genes. Gain-of-function experiments using  $H^+/K^+$ -ATPase and  $K^+$  channel overexpression also demonstrated that equalizing  $H^+$  and  $K^+$  flux on either side of the midline randomizes the LR axis.

Taken together, these data demonstrate that the *Xenopus* embryo assigns L and R identities to cells at the first few cleavages. This conclusion is also confirmed by the finding of asymmetric 14-3-3E protein localization, which is crucial for normal LR asymmetry (Bunney et al., 2003). However, a key series of experiments demonstrated that under some circumstances, ectopic organizers induced much later are still able to impose correct LR identity on nearby tissue (Nascone and Mercola, 1997). Thus, the *Xenopus* embryo is likely to contain an endogenous very early mechanism for aligning the LR axis, but also the capacity for regulatory patterning of the LR axis at later stages.

## 7. Chick

The first morphological asymmetry in the chick embryo is the tilt of Hensen's node toward the end of gastrulation (Dathe et al., 2002; Hertwig, 1902; Kölliker, 1879). Transplantation experiments in the chick had shown that heart sidedness is determined during gastrulation

(Hoyle et al., 1992), and soon thereafter the chick became the first system in which asymmetric gene expression was demonstrated. Characterizing a number of known genes during early chick embryogenesis, Levin et al. found that several had consistently asymmetric expression patterns during gastrulation and at the beginning of neurulation (Levin, 1998b; Levin et al., 1995, 1997b). Sonic hedgehog (*Shh*), a signaling molecule which is also involved in several other patterning contexts, is expressed symmetrically within the ectoderm of Hensen's node (the chick organizer [Streit et al., 1994]) before st. 4, at which time it becomes restricted to the left side of the node. This is followed at st. 7 by the left-sided expression of *Nodal* (a TGF- $\beta$  family member, originally called *cNR-1* in the chick). *Nodal* is first expressed in a small domain of endoderm cells directly adjacent to the ectoderm cells expressing *Shh*, and then in a large domain in the lateral plate mesoderm.

The juxtaposition of the proximal domain of *Nodal* to the cells expressing *Shh* suggested an inductive interaction, and indeed, implanting cells expressing *Shh* on the right side of Hensen's node is sufficient to induce an ectopic domain of *Nodal* expression on the right side. The Activin-inducible gene *Activin receptor IIa* (*cAct-RIIa*) becomes expressed on the right side of Hensen's node at the same time that *Shh* becomes restricted to the left. This suggested the right-sided presence of an Activin-like repressor upstream of *Shh*; it was then shown that a local source of Activin protein implanted on the left side is able to induce *cAct-RIIa* there, and to repress the expression of left-sided *Shh*. It is still unknown whether *cAct-RIIa* itself plays a causal role in LR patterning, but an endogenous right-sided expression of *Activin- $\beta$ B* has been reported (Levin, 1998d; Levin et al., 1997a). Many more asymmetric genes have been identified in chick embryos (Tables 2 and 3); these factors participate in cascades of induction and repression of asymmetric gene pathways taking place on the left and right of the midline, ultimately dictating heart and gut *situs* as well as embryonic turning.

The discovery that *Nodal* can positively regulate its own gene expression highlights the enduring problem of explaining how *Nodal* signaling is constrained spatially. Earlier studies, predating the elucidation of promoter elements in the *Nodal* gene, suggested the existence of a barrier at the dorsal midline of embryos to prevent signaling on one side of the embryo from interfering with cascades on the other. It has long been known, for instance, that twins conjoined at the level of the trunk often exhibit laterality disturbances and that the defects reside primarily in the right sibling. Spontaneous chick conjoined twins or experimentally induced *Xenopus* conjoined twins develop with a similar defect (Levin et al., 1996; Nascone and Mercola, 1997). Molecular genetic analyses of these embryos, however, pointed out that the defects observed in the right sibling are not due to an intrinsic error in the orientation of the LR axis, but results from interference from signals that probably originate from the right flank of the left twin.

A barrier model was proposed initially (Danos and Yost, 1995b, 1996a; King et al., 1998; Lohr et al., 1997b; Yost, 1998) to explain why interference does not occur during normal development and also to account for the severity of laterality defects seen in embryos with midline anomalies or patterning deficits created by either genetic or microsurgical means.

Possible candidates for the barrier include the primitive pit and notochord. Consistent with this, removal of the notochord destabilizes LR asymmetry (Danos and Yost, 1996b). Likewise, the *flh* ('floating head') and *ntl* ('no tail' or Brachyury) mutants have notochord defects that are often accompanied by liver and cardiac inversions (Chin et al., 2000b; Concha et al., 2000; Halpern et al., 1993; Korzh et al., 2001; Talbot et al., 1995). Molecular level insight into relatively late aspects of this important problem was provided by the discovery of Lefty homologues. Lefty proteins are divergent TGF $\beta$  superfamily ligands (Heymer et al., 1997a; Meno et al., 1996) that antagonize *Nodal* signaling in embryological assays (Bisgrove et al., 1999; Cheng et al., 2000a; Meno et al., 1999); reviewed in Schier and Shen (2000). *Lefty* genes, like *Nodal*, are implicated in LR signaling because their expression is altered by mutations that affect organ *situs* (Dufort et al., 1998; Gaio et al., 1999a; Heymer et al., 1997b; Izraeli et al., 1999; King et al., 1998; Meno et al., 1996, 1998; Meyers and Martin, 1999; Nonaka et al., 1998; Tsukui et al., 1999a; Yan et al., 1999a). Conversely, mouse embryos lacking *lefty1* have bilateral expression of normally left-sided markers, including *Nodal* (Meno et al., 1998). Given their ability to antagonize *Nodal*, *Lefty1* in the midline may provide a barrier to prevent the unwanted propagation of *Nodal* signals to the right flank of the embryo while *Lefty2* acts as a feedback inhibitor within the left lateral plate mesoderm.

The fairly dense pathway of LR cascade members in chick embryos suggests an immediate question: what mechanism is upstream of the very first asymmetrically expressed gene? Contrary to the paradigm of genetically separate L and R compartments which begins during mid-gastrulation, it was observed that events occurring on the far R side were required for establishment of L identity on the left side at the beginning of streak initiation (Levin and Mercola, 1999). Thus, gap junctional communication was examined in the chick embryo, as a candidate for a mechanism which would enable cells to communicate across large distances along the LR axis and assign LR identities to cell fields. Similarly to the results in *Xenopus*, it was discovered that differential GJC is required upstream of asymmetric *Shh* expression in the node and one Connexin, *Cx43*, was implicated by treatment with specific antisense oligonucleotides or blocking antibodies (Levin and Mercola, 1999). *Cx43* is broadly expressed in the epiblast of streak stage embryos, but not in the streak itself. Thus, GJC required for LR asymmetry may propagate signals throughout the epiblast but not across an insulating zone at the streak. In support of this model, surgical

incisions made along various radii emanating from the developing node abolish node asymmetry. While a topological transformation is required to map the GJC system onto the different embryonic architectures of the chick and *Xenopus*, the basic schematic of this system is the same in both systems: correct laterality determination upstream of asymmetric gene expression depends on an uninterrupted region of GJC around a zone of isolation.

The fact that contiguity of the blastodisc on both sides of the midline is necessary (Levin and Mercola, 1999) suggest a model whereby instructive signals traverse lateral tissue in the plane of the GJC path, which in turn predicts that the midline cells receive LR information from lateral tissue during gastrulation. In the chick, current data strongly indicates that indeed Hensen's node is instructed with respect to the LR axis by adjacent lateral cell groups (Levin and Mercola, 1999; Pagan-Westphal and Tabin, 1998; Psychoyos and Stern, 1996; Yuan and Schoenwolf, 1998), rather than generating LR information intrinsically (which would be required by the cilia-based models described below). Important open areas of research include identification of upstream signals that orient GJC in embryos, characterization of the determinants that traverse gap junctions and downstream target genes that they regulate, and the targets that are immediately downstream of GJC flow.

Because the GJC system has been shown to be conserved to both chick and *Xenopus*, a role for ion flux was tested in the chick as well (Levin et al., 2002). Analysis of the chick embryo using an *in vivo* reporter of membrane voltage indicated that cells on the left side of the primitive streak were consistently depolarized with respect to those on the contralateral side. This indicates that the chick embryo has assigned L and R identities by st. 3—prior to the earliest known asymmetric gene. Similarly to *Xenopus*, specific inhibition of the  $H^+/K^+$ -ATPase prior to gastrulation equalized the depolarization of cells across the midline, and randomized the asymmetric expression of *Shh*, *cWnt-8C*, and other markers (including *Cerberus*—a marker of head asymmetry). Interestingly, while the  $H^+/K^+$ -ATPase is expressed, as predicted by the GJC model (which requires the motive force 'battery' to be located in the zone of isolation) in the primitive streak during early gastrulation, no asymmetry in pump localization has been reported in the chick at the level of mRNA. This echoes a theme which highlights an important difference between species. While both chicks and *Xenopus* appear to use GJC and ion flux to pattern the LR axis, the regulation of the mechanisms differs. The difference in GJC in frog embryos takes place post-translationally (by gating control of existing gap junctions). In contrast, the chick embryo establishes the zone of isolation at the level of mRNA (by not transcribing *Cx43* mRNA in the primitive streak). Similarly, while asymmetric ion flux is provided by asymmetric localization of mRNA in early frog embryos, it appears to be established in the chick embryo by a post-translational mechanism

(such as gating of electrogenic activity of mature pump complexes).

While the details of ion flux in the LR pathway of other species are not yet clarified, a  $H^+$  and  $K^+$  flux appears to be conserved in sea urchin (Yuichiro Ishii et al., 2003) and *Ciona* (Shimeld, 2003). Important future data are likely to come from pursuing the asymmetric gene cascade upstream, and determining how it interfaces with the GJC and ion flux systems. Some of the details of this process have recently been provided by an elegant study which used a variety of gain- and loss-of-function approaches, together with real-time *in vivo* imaging of  $Ca^{++}$  content, to show that an  $H^+/K^+$ -ATPase-dependent extracellular calcium accumulation on the left side of Hensen's node is sensed by a *Notch* pathway mechanism (Raya et al., 2004). The epistasis between the earlier *Shh* asymmetry and the  $Ca^{++}$ -dependent *Notch* signaling is not yet clear. Raya et al. developed a mathematical model that predicts the robust *Notch* expression, and is a prototype for the kind of approach which will surely be necessary to understand and control the transduction of epigenetic factors such as ion flux into domains of stable gene expression. Does asymmetric gene expression exist prior to gastrulation? It has previously been suggested (Levin and Mercola, 1998b) that the computation which aligns the LR axis with the DV and AP axes takes place at the initiation of gastrulation, at the base of the primitive streak (which reliably progresses from the periphery to the center of the blastoderm). However, no detailed model of this process in the chick has been proposed; such a model may have to wait for an understanding of how (and whether) individual cells in the chick blastoderm determine their AP polarity (Wei and Mikawa, 2000).

## 8. Mammals

Errors of LR patterning during embryogenesis are relevant to the clinical considerations of several fairly common human birth defects: syndromes as Kartagener's and Ivemark's (Winer-Muram, 1995), dextrocardia, *situs inversus* (a complete mirror-image reversal of the sidedness of asymmetrically positioned organs and asymmetric paired organs), heterotaxia (a loss of concordance where each organ makes an independent decision as to its situs), and right or left isomerism (where the organism is completely symmetrical, for example, polysplenia or asplenia); these alterations of normal asymmetry are recapitulated in a number of animal models (Bisgrove and Yost, 2001). Of these, only the complete (and rare) *situs inversus totalis* is not associated with physiological difficulties. The rest, especially heterotaxia, often result in serious health problems for the patient (Burn, 1991). The LR asymmetry of the heart is intimately connected to its function and errors in cardiac *situs* represent a significant source of human heart disease (Kathiriyi and Srivastava, 2000). Laterality defects



can arise in a single individual (Kosaki and Casey, 1998; Winer-Muram, 1995) but are especially associated with monozygotic twinning. One interesting and poorly understood phenomenon is the relationship with sex determination: in human hermaphrodites, ovaries develop on the left, testes on the right (Mittwoch, 2000).

One of the crucial questions regarding mammalian embryos concerns when LR information is first generated. Mouse embryos have been shown to be able to reconstitute normal morphology after significant experimental manipulation—early blastomeres can be removed or added apparently without affecting normal development. This has been suggested to signify that the patterning of axes in mammalian embryos takes place later than other species such as *Xenopus*. However, a number of recent studies have suggested that the polar body may indicate the future axis of bilateral symmetry in fertilized mouse eggs (Gardner, 2001; Johnson, 2001), perhaps indicating the existence of early axial orientation mechanisms that could be masked by later regulation in the event of experimental perturbation.

The observation that human Kartagener's syndrome patients exhibited randomization of visceral *situs* (heterotaxia) and had ultrastructural defects in the dynein component of cilia (Afzelius, 1976, 1985) was of great interest because it suggested that asymmetry could be bootstrapped from molecular chirality of some ciliary component. This idea was supported by the finding that the murine *iv* mutation, which unbiases laterality (Lowe et al., 1996b; Schreiner et al., 1993; Singh et al., 1991), encodes a dynein called left–right dynein (LRD) that is expressed in cells of the mouse node (Supp et al., 1997). Axonemal dynein is a component of the motor which drives ciliary motion; the chirality of this motion is intrinsic to the protein components. Genetic deletions of KIF3-A or KIF3-B (Marszalek et al., 1999; Nonaka et al., 1998), two microtubule-dependent kinesin motor proteins, resulted in defects in nodal cilia and randomization of the *situs* of the viscera, and this finding provides evidence for a role for cilia in LR determination (Vogan and Tabin, 1999). Most importantly, following the first observation of cilia in the murine node (Sulik et al., 1994), elegant and technologically challenging experiments have revealed a clockwise rotation of monocilia extending ventral to the node that produces a localized net right to left fluid flow of fluorescent beads placed in the extra-embryonic space (Nonaka et al., 1998; Okada et al., 1999; Takeda et al., 1999b). Thus, it was proposed that vortical action of cilia (coupled with the wedge-shape of the node) may initiate asymmetry by moving an extracellular signaling molecule to one side, where it can induce asymmetric gene expression (Vogan and Tabin, 1999). A more sophisticated version of this model, invoking two kinds of cilia (motile and sensory) was later proposed, to account for discrepancies between data from observations of ciliary beating in cultured mouse embryos, and the molecular and morphological phenotype observed in the LR mutants (McGrath and Brueckner, 2003;

Tabin and Vogan, 2003). In addition to Kinesin and Dynein, a number of other proteins have also been linked to asymmetry which have been interpreted to result from impaired ciliary function. These include Inversin (Morgan et al., 1998, 2002; Otto et al., 2003; Watanabe et al., 2003), Polaris (Murcia et al., 2000; Taulman et al., 2001), and Polycystin-2 (Pennekamp et al., 2002).

The strongest version of this model (McGrath et al., 2003) hypothesizes that LR asymmetry is initiated by the motion of the cilia in the mature node (toward the end of gastrulation). A recent set of intricate experiments demonstrated that artificial flow around the cultured node of rodent embryos is able to affect asymmetry. While the results of a 'no flow' condition (such as in viscous medium) have not been demonstrated, and culture of rodent embryos randomizes *situs* in and of itself (Fujinaga and Baden, 1991; Fujinaga et al., 1990), these data demonstrate that in rodent embryos cilia at the node are likely to play a functional role in the LR pathway, although it is not known whether they generate LR information *de novo*, or function in transmission of upstream LR signals. Consistent with the theoretically pleasing hypothesis that cilia initiate LR orientation, no earlier LR mechanisms have yet been described in rodents. However, many types of cilia can reverse the direction of their beat (Bone, 1958), and it is not yet clear whether the biochemical structure of cilia uniquely determines their function (allowing asymmetry to be generated from molecular chirality). Because rodent embryos in which molecular motors have been mutated are also likely to have impaired cytoplasmic function of motor transport, it has not yet been possible to separate the ciliary functions of the LR-relevant motors from cytoplasmic transport roles.

The rodent embryo is quite unusual in its large-scale and node architecture, compared to most mammals. However, consistent with the possibility that the relationship between cilia and asymmetry is not unique to rodents, a recent study in Zebrafish demonstrated that knock-down of the *ntl* gene specifically in the dorsal fore-runner cells (ciliated cells in Kupffer's vesicle) results in randomization of *situs* (Amack and Yost, 2004). While these data do not address the role of the cilia *per se*, they do suggest that the role of *ntl* in asymmetry is not confined to midline barrier function, and indicate that the dorsal fore-runner cells are a crucial component of the LR pathway in zebrafish. While a function for motor proteins in LR patterning is fairly certain, the mechanisms by which they control laterality and whether cilia *per se* contribute to the initiation or transmission of asymmetry in each species remains controversial (Hamada et al., 2002; Levin, 2003b, 2004a,b).

The earliest known endogenous LR mechanisms (GJC,  $H^+/K^+$  flux, Vg1 coordinator) have not been found to contribute to mammalian asymmetry. However, ion flux has been implicated in mouse embryos. A genetic deletion experiment has suggested that the ion channel Polycystin is required for normal asymmetry in the mouse (Pennekamp

et al., 2002). More directly, it has recently been shown that asymmetric calcium signaling appears at the left margin of the node at the time of nodal flow (McGrath et al., 2003); this cytoplasmic  $\text{Ca}^{++}$  gradient may be analogous to the extracellular  $\text{Ca}^{++}$  flux recently demonstrated in the chick (Raya et al., 2004). Whether additional ion flows play a role in rodents and other mammals, and whether  $\text{Ca}^{++}$  flow is important for LR patterning prior to mature node stages, remains uncertain.

Rabbit embryos (like most mammals including human embryos) develop as a flat blastodisc similar to the chick, and have contributed significant advances which complement and contrast mouse data (Fischer et al., 2002; Viebahn, 2001; Viebahn et al., 1995). Indeed, mice may not recapitulate all phenomena important for LR patterning. For example, the striking strict one-sided midline pigment lateralization observed in human children affected by CHILD (Happle, 2002; Happle et al., 1995; Konig et al., 2000) syndrome is not seen in the corresponding mouse mutant (Liu et al., 1999; Phillips et al., 1973), suggesting that important aspects of early gene function and demarcation of the LR midline may differ between rodents and other mammals. This becomes of particular importance when considering the mechanistic implications of laterality phenotypes observed in human monozygotic twins (below). Moreover, while mice do exhibit the strong linkage between sidedness of hermaphroditic organs observed in human cases (Biddle et al., 1994; Eicher and Washburn, 1983; Ward et al., 1987), the consistent laterality of testes' vs. ovaries' placement is opposite of that observed in humans (Krob et al., 1994; van Niekerk and Retief, 1981). Tractable mouse models of these fascinating phenomena may not always be possible, and may not provide data directly applicable to human development.

## 9. Twinning and asymmetry

Inversions of various organs have been observed in the context of human conjoined twins (Aird, 1959; Cuniff et al., 1988; Torgersen, 1950). It is also known that conjoined twins of armadillo (Newman, 1916), fish (Morrill, 1919), frog (Spemann and Falkenberg, 1919), and man (Burn, 1991; Winer-Muram, 1995), often exhibit alterations of *situs* in one of the twins. The discovery of the spatial signals propagated by asymmetric gene expression in chick embryos have allowed a partial understanding of laterality defects in human conjoined twins (Kapur et al., 1994). Analysis of spontaneous twins of chick embryos in various orientations suggests that laterality defects in one twin may be induced by cross-over of LR morphogen molecules from the adjacent twin (Levin et al., 1996). More detail is provided in Supplement 1.

Non-conjoined monozygotic twins, while not exhibiting the kinds of visceral laterality defects that occur in conjoined twins, do manifest many subtler kinds of

mirror-image asymmetry ('bookend' or enantiomer twin pairs). Pairs of such twins have been noted to present mirror asymmetries in hand preference, hair whorl direction, tooth patterns, unilateral eye and ear defects, cleft lip, cleft palate, supernumerary teeth, and even tumor locations and undescended testicles (Beere et al., 1990; Carton and Rees, 1987; Cidis et al., 1997; Gedda et al., 1981; Lauterbach, 1925; Mensing, 1983; Morini et al., 2002; Morison et al., 1994; Newman et al., 1937; Okamoto et al., 2001; Potter and Nance, 1976; Rife, 1933, 1940, 1980; Satoh et al., 1995; Schneider, 1985; Sommer et al., 1999, 2002; Sperber et al., 1994; Townsend and Richards, 1990; West, 1985; Yager, 1984). The mirror/bookending phenomenon also pertains to functional parameters such as sleep deviations, and hearing and cerebral functional localization (Golbin et al., 1993; Sommer et al., 1999, 2002; Springer and Searleman, 1978a,b).

Interestingly, though monozygotic twins affected by genetic lesions often show opposite sidedness of limb abnormalities (Opitz and Utkus, 2001; Richieri-Costa and Opitz, 1986), almost all bookending phenomena in healthy twins involve features of the head. Thus, consistently with the discordance between brain and body *situs* discussed above, there may be two separate organizers for the head and body (Meinhardt, 2002), which use different mechanisms of determining laterality (Harland and Gerhart, 1997). The bookending phenomenon may also speak to the timing of the earliest steps of asymmetry in mammals. Most healthy, non-conjoined twins presumably result from separation of cleavage, morula, or early blastocyst stage embryos (James, 1983). Thus, some chiral information may be present in the very early mammalian embryo, later manifesting as hair whorls, etc. if the cells are separated at an early stage. In contrast, the asymmetry of the major body organs seems to be unspecified (or plastic enough to be re-specified) at those stages, and is developed correctly for both monozygotic twins. This may be related to the fact that heterotaxic reversals in hair whorls and tooth patterns would not be expected to be disadvantageous, while discordant *situs* for internal organs clearly is subject to negative evolutionary pressure. An alternative model is that some as yet unknown pathological mechanism is responsible for both the process of twinning itself and the destabilization of the LR axis (Boklage, 1981, 1987). In support of this view, it has been found that increased incidence of left-handedness in twins is not dependent on zygosity or time of splitting (Derom et al., 1996; McManus and Bryden, 1992). The molecular basis of these phenomena is not understood, although analysis of laterality in twins produced by splitting of embryos during in vitro fertilization procedures may eventually provide important clues. Interestingly, monozygotic twins are often discordant for the imprinting of KCNQ1 (Weksberg et al., 2002), a potassium channel which has been implicated in LR asymmetry in frog embryos (Levin, 2003a).



## 10. Laterality and brain asymmetry

Nervous system lateralization is spread throughout evolution (Andrew, 2000), while some animals (e.g. mice) often show paw preference, the consistent preference among all individuals only approaches high levels in man (approximately 90% for right-handedness). The genetic basis of handedness in man is still highly controversial (McManus, 1995; McManus and Bryden, 1992). Left-handedness runs in families weakly—almost half of all left-handers have no known left-handed relatives (McManus, 1995). Two right-handed parents have left-handed children in about 5–10% of the cases, while two left-handed parents have left-handed children in about 25–30% of cases (McManus and Bryden, 1992). Monozygotic twins often differ in their handedness.

Interestingly, it has been found that brain asymmetry does not correlate with visceral asymmetry (Kennedy et al., 1999; Tanaka et al., 1999). For example, *situs inversus totalis* individuals still have language lateralization seen in 95% of right-handed normal *situs* individuals (Kennedy et al., 1999). The incidence of left-handedness is the same in *situs inversus* individuals as in the rest of the population (Cockayne, 1938; Torgersen, 1950). This suggests that mechanisms establishing the laterality of the brain are, at some early point in the LR pathway, different from those which determine the sidedness of visceral organs. Moreover, human patients with primary ciliary dyskinesia (and the attendant heterotaxia) do not exhibit reversals in the normal prevalence of right-handedness (McManus et al., 2004), suggesting that at least some aspects of laterality in humans are indeed upstream of mutations affecting ciliary function.

## 11. Conservation of mechanisms

While a number of mechanisms (e.g. apoptosis, syndecans) have only been implicated in one species (chick and frog respectively), others (e.g. Vg-1, GJC, ion flux, Notch) appear to be more widely conserved. Indeed, a relationship with the LR axis of  $Ca^{++}$  flux for example appears to be conserved in invertebrates, chicks, and mice (Albrieux and Villaz, 2000; McGrath et al., 2003; Raya et al., 2004). Important differences exist, however, in the details of a number of pathways. For example, in chick, *Shh* is a left-sided determinant while *Fgf-8* is a right-sided signal (Boettger et al., 1999; Levin et al., 1995), while in mouse *Fgf-8* appears to determine the left side identity while *Shh* is necessary to confine left-sided proteins to the left (Meyers and Martin, 1999). Interestingly, the details of these pathways appear to be correlated with the geometry of embryogenesis rather than taxonomy. In rabbit (a mammal which might be expected to utilize *Fgf-8* as a left determinant as does the mouse), *Fgf-8* is a right side molecule, suggesting that the flat blastodisc, a feature shared

by rabbit and chick embryos, may be the important parameter (Fischer et al., 2002). A similar inversion between chick and mouse is observed with respect to the gene *NKX3.2* (Schneider et al., 1999).

One crucial open question in the field concerns the conservation of the early members of the asymmetric gene cascade. The earliest conserved asymmetric gene known is *Nodal*, which is left-sided at somite stages in all vertebrates in which it has been examined. Downstream *Lefty* and *Pitx-2* genes appear to be well conserved also. However, neither *Shh* nor any of the other early genes known to be asymmetric during chick gastrulation (*cAct-RIIa*, *cHNF3-β*, *Follistatin*, *cWnt-8C*, etc.) have been reported to asymmetric in other species despite in situ hybridization searches by a number of labs (Ekker et al., 1995; Stolow and Shi, 1995), although *Shh* is left-sided in ducks and quails (Levin, 1996). Interestingly, misexpression of Hedgehog proteins in frog embryos is known to randomize asymmetry (Sampath et al., 1997), raising the possibility that the asymmetric Hedgehog signal exists in amphibia but perhaps utilizes an as yet uncharacterized family member. The situation with respect to the early asymmetric genes is the same in mouse, where genetic deletions have suggested roles for some of the same molecules (Oh and Li, 1997; Tsukui et al., 1999b). It is possible that the asymmetry in Hedgehog signaling exists at a level other than mRNA (protein processing, translation, etc.) or is anatomically so subtle as to have been missed. While no asymmetric expression upstream of *Nodal* has been reported in mice, two mouse pathways (the first conserved to chicks, the second to *Xenopus*) play a role upstream of *Nodal*: the *Notch* pathway (Krebs et al., 2003; Raya et al., 2003b) and *Vg-1* (Rankin et al., 2000). Two more areas which are of relevance to questions of evolutionary conservation are retinoic acid signaling and induction of *Nodal* genes by *Hedgehog* signals in amphibia; details can be found in Supplement 2.

## 12. Open questions

An interesting aspect of *Nodal* expression in *Xenopus* concerns the degree of bias of asymmetry. In both chick and mouse, the left-sided expression of *Nodal* is observed in all normal embryos (Collignon et al., 1996; Levin et al., 1995; Lowe et al., 1996b). In contrast, left-sided expression of xNR-1 in the frog is quite variable, being undetectable in up to 25% of the embryos, even from groups whose other members go on to form late-stage tadpoles with 100% normal LR asymmetry (Levin and Mercola, 1998c; Lohr et al., 1997b). Nevertheless, *Nodal* is a common left-sided mid-pathway asymmetric gene in all model systems to date; understanding the evolutionary mechanisms which resulted in this stable point, together with divergence of upstream mechanisms (if indeed they differ), is a key challenge.

Most of the work in the LR field has naturally addressed the mechanisms controlling the *situs* of morphologically

asymmetric organs. However, the human and rodent data discussed above (unilateral drug effects and global hemihypertrophy syndromes) indicate that seemingly identical paired structures may in fact harbor subtle molecular differences conferring positional information along the LR axis, and that this information may persist well into adulthood. Recent studies have indicated that rodent embryo somites exhibit a striking asymmetric expression of genes such as HB-EGF and MLC3F (Golding et al., 2004a,b); differential gene expression in precursors of paired organs and skeletal elements could potentially provide a heretofore unsuspected mechanism for assigning L and R identity to seemingly identical structures (such as limbs). Future work must characterize novel molecular differences between paired structures and address the functional significance of this asymmetric gene expression. Identification of LR signals in locales other than overtly asymmetric organs, and an understanding of the temporal persistence of LR information after embryogenesis, are sure to have important implications for biomedicine and basic developmental biology.

Because no macroscopic force distinguishes right from left, a powerful paradigm has been proposed to leverage large-scale asymmetry from the chirality of sub-cellular components (Brown et al., 1991; Brown and Wolpert, 1990). In this class of models, some molecule or organelle with a fixed chirality is oriented with respect to the antero-posterior and DV axes, and its chiral nature is thus able to nucleate asymmetric processes such as transport (Levin and Mercola, 1998a). Thus, the first developmental event which distinguishes left from right would take place on a subcellular scale. However, a mechanism must then exist to transduce subcellular signals to cell fields (Levin and Mercola, 1998a; Levin and Nascone, 1997). Asymmetric gene expression in embryos requires that fairly large fields of cells already know on which side of the midline they are located (such as the expression of the left-sided gene *Nodal*). In contrast, proposed mechanisms of step 1 of asymmetry (such as the F-molecule model) rely on subcellular mechanisms for determining which direction is Left and which is Right. Thus, one of the key questions concerns how orientation information can be turned into information on a cell's location, relative to the midline, within the context of the whole embryo. This information flow must take place between cells; ciliary motion driving extracellular flow of signaling molecules and cell–cell communication via gap junctions are both natural candidates for such a signal exchange. Roles for epigenetic factors such as membrane voltage, and  $Ca^{++}$  signaling are also likely.

One of the key remaining questions is the molecular meaning of 'randomization'. Upon the initial discovery of the LR pathway, it was observed that embryos with double-sided *Nodal* expression or lack of *Nodal* expression (produced by *Shh* or *Activin* implants, respectively), show a randomization of visceral *situs* (Levin et al., 1995, 1997b)—not a loss of asymmetry in the heart and gut, but heterotaxia. This was interpreted as suggesting that this

pathway of genes imparts LR information to the organs but does not control their morphogenesis per se, leading the organs to independently and randomly choose their *situs* when presented with identical molecular signals from the L and R sides. However, it is now known that global equalization of signaling in a number of LR pathways including GJC, H,K-ATPase, and apoptosis, also induce *randomization* of asymmetric genes such as *Shh*. A mechanistic model for this process would have to explain not simply consistent induction (or repression) of genes such as *Shh* by gap junctional communication or cell depolarization, but a mechanism by which cells in both sides of the node can be driven to randomly express *Shh* or not. Even more puzzling for simple gene cascade models is the observation that in several vertebrate and invertebrate systems, symmetrization of an upstream asymmetric gene does not lead to uniformly bilateral or missing expression of downstream genes (in the case of positive and negative regulation, respectively) but rather results in a randomization of downstream gene expression (Morokuma et al., 2002), or does not affect downstream LR pathway targets at all (Kelly et al., 2002). One candidate for such a bistable mechanism would be a short-range activation/long-range inhibition system such as that which establishes cell polarity via the Notch-Delta pathway. Interestingly, a role for this pathway has recently been implicated downstream of the H,K-ATPase in the chick (Raya et al., 2004). Thus, it is possible that such a mechanism works in the node to integrate a number of epigenetic biasing factors into stable domains of downstream gene expression. Future work is necessary to understand how this works in the node and streak; recent mathematical models are beginning to tackle this issue (Meinhardt and Gierer, 2000; Rasskin-Gutman and Izpisua-Belmonte, 2004); potential candidate molecules may include motor proteins from the kinesin family gene which could underlie intracellular transport in node signaling events (Dathe et al., 2004).

### 13. Conclusion

The consistent macroscopic chirality of embryonic structures is a crucial part of developmental biology. This question touches on issues ranging from evolutionary mechanisms of body-plan dynamics to the subtleties of parity conservation in quantum mechanics (see Supplement 3 which discusses the possible relationship of macroscopic LR asymmetry with chemical chirality). While a number of important advances have been made in several model systems, the most interesting questions remain open. It is likely that future experiments addressing the role of motor proteins, small molecule movement, and the mechanisms which generate organ shape from laterality signals, will open new areas of cell, developmental, and evolutionary biology.

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## Appendix. Supplementary material

Supplementary data associated with this article can be found, in the online version, at [doi:10.1016/j.mod.2004.08.006](https://doi.org/10.1016/j.mod.2004.08.006)

## References

- Adam, G., Perrimon, N., Noselli, S., 2003. The retinoic-like juvenile hormone controls the looping of left–right asymmetric organs in *Drosophila*. *Development* 130, 2397–2406.
- Adams, D.S., Levin, M., 2003. Elements of left–right patterning gap junctions, pH, and membrane voltage. *Dev. Biol.* 259, 482–483.
- Afzelius, B., 1976. A human syndrome caused by immotile cilia. *Science* 193, 317–319.
- Afzelius, B., 1985. The immotile cilia syndrome: a microtubule-associated defect. *CRC Crit. Rev. Biochem.* 19, 63–87.
- Aihara, M., Amemiya, S., 2000. Inversion of left–right asymmetry in the formation of the adult rudiment in sea urchin larvae: removal of a part of embryos at the gastrula stage. *Zygote* 8 (Suppl. 1), S82–S83.
- Aihara, M., Amemiya, S., 2001. Left–right positioning of the adult rudiment in sea urchin larvae is directed by the right side. *Development* 128, 4935–4948.
- Aird, I., 1959. Conjoined twins. *Br. Med. J.* 1, 1313–1315.
- Albrieux, M., Villaz, M., 2000. Bilateral asymmetry of the inositol trisphosphate-mediated calcium signaling in two-cell ascidian embryos. *Biol. Cell* 92, 277–284.
- Amack, J.D., Yost, H.J., 2004. The T box transcription factor no tail in ciliated cells controls zebrafish left–right asymmetry. *Curr. Biol.* 14, 685–690.
- Andrew, R.J., 2000. The earliest origins and subsequent evolution of lateralisation, in: Rogers, L.J., Andrew, R.J. (Eds.), *Comparative Vertebrate Lateralisation*. Cambridge University Press, Cambridge.
- Angelo, S., Lohr, J., Lee, K.H., Ticho, B.S., Breitbart, R.E., Hill, S., et al., 2000. Conservation of sequence and expression of *Xenopus* and zebrafish dHAND during cardiac, branchial arch and lateral mesoderm development. *Mech. Dev.* 95, 231–237.
- Araki, I., Terazawa, K., Satoh, N., 1996. Duplication of an amphioxus myogenic *Bhlh* gene is independent of vertebrate myogenic *Bhlh* gene duplication. *Gene* 171, 231–236.
- Bamford, R.N., Roessler, E., Burdine, R.D., Saplakoglu, U., dela Cruz, J., Splitt, M., et al., 2000. Loss-of-function mutations in the EGF-CFC gene *CFC1* are associated with human left–right laterality defects. *Nat. Genet.* 26, 365–369.
- Barr, M., 1973. The teratogenicity of cadmium chloride in two stocks of Wistar rats. *Teratology* 7, 237–242.
- Beere, D., Hargreaves, J., Sperber, G., Cleaton-Jones, P., 1990. Mirror image supplemental primary incisor teeth in twins: case report and review. *Pediatr. Dent.* 12, 390–392.
- Biben, C., Harvey, R., 1997. Homeodomain factor *Nkx2-5* controls left/right asymmetric expression of *bHLH* gene *eHand* during murine heart development. *Genes. Dev.* 11, 1357–1369.
- Biddle, F.G., Eisner, J.R., Eales, B.A., 1994. The testis-determining autosomal trait, *Tda-1*, of *C57BL/6J* is determined by more than a single autosomal gene when compared with *DBA/2J* mice. *Genome* 37, 296–304.
- Bisazza, A., de Santi, A., 2003. Lateralization of aggression in fish. *Behav. Brain Res.* 141, 131–136.
- Bisgrove, B.W., Yost, H.J., 2001. Classification of left–right patterning defects in zebrafish, mice, and humans. *Am. J. Med. Genet.* 101, 315–323.
- Bisgrove, B., Essner, J., Yost, H., 1999. Regulation of midline development by antagonism of lefty and nodal signaling. *Development* 126, 3253–3262.
- Bochert, G., Platzek, T., Blankenburg, G., Wiessler, M., Neubert, D., 1985. Embryotoxicity induced by alkylating agents: left-sided preponderance of paw malformations induced by acetoxymethyl-methylnitrosamine in mice. *Arch. Toxicol.* 56, 139–155.
- Boettger, T., Wittler, L., Kessel, M., 1999. *FGF8* functions in the specification of the right body side of the chick. *Curr. Biol.* 9, 277–280.
- Boklage, C.E., 1981. On the timing of monozygotic twinning events. *Prog. Clin. Biol. Res.* 69A, 155–165.
- Boklage, C.E., 1987. Twinning, nonrighthandedness, and fusion malformations: evidence for heritable causal elements held in common. *Am. J. Med. Genet.* 28, 67–84.
- Bone, Q., 1958. Observations upon the living larva of amphioxus. *Publicazioni Stazione Zoologica di Napoli* 30, 458–471.
- Boorman, C.J., Shimeld, S.M., 2002a. The evolution of left–right asymmetry in chordates. *Bioessays* 24, 1004–1011.
- Boorman, C.J., Shimeld, S.M., 2002b. *Pitx* homeobox genes in *Ciona* and amphioxus show left–right asymmetry is a conserved chordate character and define the ascidian adenypharynx. *Evol. Dev.* 4, 354–365.
- Branford, W.W., Essner, J.J., Yost, H.J., 2000. Regulation of gut and heart left–right asymmetry by context-dependent interactions between *xenopus* lefty and *BMP4* signaling. *Dev. Biol.* 223, 291–306.
- Britz-Cunningham, S., Shah, M., Zuppan, C., Fletcher, W., 1995. Mutations of the *connexin-43* gap-junction gene in patients with heart malformations and defects of laterality. *N. Engl. J. Med.* 332, 1323–1329.
- Brizuela, B.J., Wessely, O., De Robertis, E.M., 2001. Overexpression of the *Xenopus* tight-junction protein claudin causes randomization of the left–right body axis. *Dev. Biol.* 230, 217–229.
- Brody, S.L., Yan, X.H., Wuerffel, M.K., Song, S.K., Shapiro, S.D., 2000. Ciliogenesis and left–right axis defects in forkhead factor *HFH-4*-null mice. *Am. J. Respir. Cell Mol. Biol.* 23, 45–51.
- Brown, N., Wolpert, L., 1990. The development of handedness in left/right asymmetry. *Development* 109, 1–9.
- Brown, N., McCarthy, A., Wolpert, L., 1991. Development of handed body asymmetry in mammals. *CIBA Found. Symp.* 162, 182–196.
- Bruneau, B.G., Logan, M., Davis, N., Levi, T., Tabin, C.J., Seidman, J.G., Seidman, C.E., 1999. Chamber-specific cardiac expression of *Tbx5* and heart defects in Holt-Oram syndrome. *Dev. Biol.* 211, 100–108.
- Bunney, T.D., De Boer, A.H., Levin, M., 2003. Fusicocin signaling reveals 14-3-3 protein function as a novel step in left–right patterning during amphibian embryogenesis. *Development* 130, 4847–4858.
- Burdine, R., Schier, A., 2000. Conserved and divergent mechanisms in left–right axis formation. *Genes Dev.* 14, 763–776.
- Burn, J., 1991. Disturbance of morphological laterality in humans. *CIBA Found. Symp.* 162, 282–296.
- Carton, A., Rees, R., 1987. Mirror image dental anomalies in identical twins. *Br. Dent. J.* 162, 193–194.
- Chen, I., Levin, M., 2004. The role of *KATP* channels in development of left–right asymmetry in *Xenopus*. *J. Dent. Res.* 83, A1340.
- Chen, J., Eeden, F.V., Warren, K., Chin, A., Nusslein-Volhard, C., Haffter, P., Fishman, M., 1997. Left–right pattern of cardiac *BMP4* may drive asymmetry of the heart in zebrafish. *Development* 124, 4373–4382.

- Chen, J., Knowles, H.J., Hebert, J.L., Hackett, B.P., 1998. Mutation of the mouse hepatocyte nuclear factor/forkhead homologue 4 gene results in an absence of cilia and random left–right asymmetry. *J. Clin. Invest.* 102, 1077–1082.
- Cheng, A., Thisse, B., Thisse, C., Wright, C., 2000a. The lefty-related factor *Xatv* acts as a feedback inhibitor of nodal signaling in mesoderm induction and L–R axis development in *xenopus*. *Development* 127, 1049–1061.
- Cheng, A.M., Thisse, B., Thisse, C., Wright, C.V., 2000b. The lefty-related factor *Xatv* acts as a feedback inhibitor of nodal signaling in mesoderm induction and L–R axis development in *xenopus*. *Development Suppl.* 127, 1049–1061.
- Chin, A.J., Tsang, M., Weinberg, E.S., 2000a. Heart and gut chiralities are controlled independently from initial heart position in the developing zebrafish. *Dev. Biol.* 227, 403–421.
- Chin, A.J., Tsang, M., Weinberg, E.S., 2000b. Heart and gut chiralities are controlled independently from initial heart position in the developing zebrafish. *Dev. Biol.* 227, 403–421.
- Cidis, M., Warshowsky, J., Goldrich, S., Meltzer, C., 1997. Mirror-image optic nerve dysplasia with associated anisometropia in identical twins. *J. Am. Ptometry Assoc.* 68, 325–329.
- Clericuzio, C.L., 1993. Clinical phenotypes and Wilms tumor.[comment]. *Med. Pediatr. Oncol.* 21, 182–187.
- Cockayne, E., 1938. The genetics of transposition of the viscera. *Quarterly J. Med.* 31, 479–493.
- Collignon, J., Varlet, I., Robertson, E., 1996. Relationship between asymmetric nodal expression and the direction of embryonic turning. *Nature* 381, 155–158.
- Concha, M.L., Burdine, R.D., Russell, C., Schier, A.F., Wilson, S.W., 2000. A nodal signaling pathway regulates the laterality of neuroanatomical asymmetries in the zebrafish forebrain. *Neuron* 28, 399–409.
- Concha, M.L., Russell, C., Regan, J.C., Tawk, M., Sidi, S., Gilmour, D.T., et al., 2003. Local tissue interactions across the dorsal midline of the forebrain establish CNS laterality. *Neuron* 39, 423–438.
- Constam, D., Robertson, E., 2000. Tissue-specific requirements for the proprotein convertase *Furin/SPC1* during embryonic turning and heart looping. *Development* 127, 245–254.
- Cooke, J., 2004. Developmental mechanism and evolutionary origin of vertebrate left/right asymmetries. *Biol. Rev. Camb. Philos. Soc.* 79, 377–407.
- Cserjesi, P., Brown, D., Lyons, G., Olson, E., 1995. Expression of novel basic Helix-Loop-Helix gene *eHAND* in neural crest derivatives and extraembryonic membranes during mouse development. *Dev. Biol.* 170, 664–678.
- Cuniff, C., Jones, K., Jones, M., Saunders, B., Shepard, T., Benirschke, K., 1988. Laterality defects in conjoined twins: implications for normal asymmetry in human embryogenesis. *Am. J. Med. Genet.* 31, 669–677.
- Danos, M., Yost, H., 1995a. Linkage of cardiac left–right asymmetry and dorsal-anterior development in *Xenopus*. *Development* 121, 1467–1474.
- Danos, M.C., Yost, H.J., 1995b. Linkage of cardiac left–right asymmetry and dorsal-anterior development in *Xenopus*. *Development Suppl.* 121, 1467–1474.
- Danos, M., Yost, H., 1996a. Role of notochord in specification of cardiac left–right orientation in zebrafish and *Xenopus*. *Dev. Biol.* 177, 96–103.
- Danos, M.C., Yost, H.J., 1996b. Role of notochord in specification of cardiac left–right orientation in zebrafish and *Xenopus*. *Dev. Biol.* 177, 96–103.
- Dathe, V., Gamel, A., Manner, J., Brand-Saberi, B., Christ, B., 2002. Morphological left–right asymmetry of Hensen’s node precedes the asymmetric expression of *Shh* and *Fgf8* in the chick embryo. *Anat. Embryol.* 205, 343–354.
- Dathe, V., Prots, F., Brand-Saberi, B., 2004. Expression of kinesin *kif5c* during chick development. *Anat. Embryol(Berlin)* 2004;.
- Delattre, M., Felix, M.A., 2001. Development and evolution of a variable left–right asymmetry in nematodes: the handedness of P11/P12 migration. *Dev. Biol.* 232, 362–371.
- Derom, C., Thiery, E., Vlietinck, R., Loos, R., Derom, R., 1996. Handedness in twins according to zygosity and chorion type: a preliminary report. *Behav. Genet.* 26, 407–408.
- Dufort, D., Schwartz, L., Harpal, K., Rossant, J., 1998. The transcription factor *HNFB3beta* is required in visceral endoderm for normal primitive streak morphogenesis. *Development* 125, 3015–3025.
- Eicher, E.M., Washburn, L.L., 1983. Inherited sex reversal in mice: identification of a new primary sex-determining gene. *J. Exp. Zool.* 228, 297–304.
- Ekker, S.C., McGrew, L.L., Lai, C.J., Lee, J.J., von Kessler, D.P., Moon, R.T., Beachy, P.A., 1995. Distinct expression and shared activities of members of the hedgehog gene family of *Xenopus laevis*. *Development Suppl.* 121, 2337–2347.
- Endress, P., 1999. Symmetry in flowers: diversity and evolution. *Int. J. Plant Sci.* 160, S3–S23.
- Endress, P.K., 2001. Evolution of floral symmetry. *Curr. Opin. Plant Biol.* 4, 86–91.
- Essner, J.J., Branford, W.W., Zhang, J., Yost, H.J., 2000. Mesendoderm and left–right brain, heart and gut development are differentially regulated by *pitx2* isoforms. *Development Suppl.* 127, 1081–1093.
- Faisst, A.M., Alvarez-Bolado, G., Treichel, D., Gruss, P., 2002. *Rotatin* is a novel gene required for axial rotation and left–right specification in mouse embryos. *Mech. Dev.* 113, 15–28.
- Falk, M.M., 2000. Biosynthesis and structural composition of gap junction intercellular membrane channels. *Eur. J. Cell Biol.* 79, 564–574.
- Fernandez-Teran, M., Piedra, M.E., Kathiriya, I.S., Srivastava, D., Rodriguez-Rey, J.C., Ros, M.A., 2000. Role of *dHAND* in the anterior–posterior polarization of the limb bud: implications for the Sonic hedgehog pathway. *Development Suppl.* 127, 2133–2142.
- Fischer, A., Viebahn, C., Blum, M., 2002. *FGF8* Acts as a right determinant during establishment of the left–right axis in the rabbit. *Curr. Biol.* 12, 1807–1816.
- Flagg-Newton, J.L., Loewenstein, W.R., 1980. Asymmetrically permeable membrane channels in cell junction. *Science* 207, 771–773.
- Frankel, J., 1991. Intracellular handedness in ciliates. *Ciba Found. Symp.* 162, 73–88.
- Fraumeni Jr., J.F., Geiser, C.F., Manning, M.D., 1967. Wilms’ tumor and congenital hemihypertrophy: report of five new cases and review of literature. *Pediatrics* 40, 886–899.
- Freeman, G., Lundelius, J., 1982. The developmental genetics of dextrality and sinistrality in the gastropod *Lymnaea peregra*. *Wilhelm Roux’s Arch.* 191, 69–83.
- Fujinaga, M., Baden, J.M., 1991. Evidence for an adrenergic mechanism in the control of body asymmetry. *Dev. Biol.* 143, 203–205.
- Fujinaga, M., Baden, M.J., 1993a. *Teratology* 47, 419a.
- Fujinaga, M., Baden, M.J., 1993b. *Teratology* 47, 418a.
- Fujinaga, M., Baden, J.M., Shepard, T.H., Mazze, R.I., 1990. Nitrous oxide alters body laterality in rats. *Teratology* 41, 131–135.
- Fukumoto, T., Kema, I., Nazarenko, D., Levin, M., 2003. Serotonin is a novel very early signaling mechanism in left–right asymmetry. *Dev. Biol.* 259, 490.
- Gaio, U., Schweickert, A., Fischer, A., Garratt, A., Muller, T., Ozcelik, C., et al., 1999a. A role of the cryptic gene in the correct establishment of the left–right axis. *Curr. Biol.* 9, 1339–1342.
- Gaio, U., Schweickert, A., Fischer, A., Garratt, A.N., Muller, T., Ozcelik, C., et al., 1999b. A role of the cryptic gene in the correct establishment of the left–right axis. *Curr. Biol.* 9, 1339–1342.
- Gamse, J.T., Thisse, C., Thisse, B., Halpern, M.E., 2003. The parapineal mediates left–right asymmetry in the zebrafish diencephalon. *Development* 130, 1059–1068.
- Garcia-Castro, M., Vielmetter, E., Bronner-Fraser, E., 2000. N-cadherin, a cell adhesion molecule involved in establishment of embryonic left–right asymmetry. *Science* 288, 1047–1051.
- Gardner, R.L., 2001. Specification of embryonic axes begins before cleavage in normal mouse development. *Development Suppl.* 128, 839–847.

- Gebbia, M., Ferrero, G., Pilia, G., Bassi, M., Aylsworth, A., Penmansplitt, M., et al., 1997. X-linked situs abnormalities result from mutations in ZIC3. *Nat. Genet.* 17, 305–308.
- Gedda, L., Brenci, G., Franceschetti, A., Talone, C., Ziparo, R., 1981. Study of mirror imaging in twins. *Prog. Clin. Biol. Res.* 69A, 167–168.
- Gerhart, J., Danilchik, M., Doniach, T., Roberts, S., Rowning, B., Stewart, R., 1989. Cortical rotation of the *Xenopus* egg: consequences for the anteroposterior pattern of embryonic dorsal development. *Development Suppl.* 107, 37–51.
- Gilland, E., Miller, A.L., Karplus, E., Baker, R., Webb, S.E., 1999. Imaging of multicellular large-scale rhythmic calcium waves during zebrafish gastrulation. *Proc. Natl Acad Sci. USA.* 96, 157–161.
- Golbin, A., Golbin, Y., Keith, L., Keith, D., 1993. Mirror imaging in twins: biological polarization—an evolving hypothesis. *Acta Geneticae Medicae et Gemellologiae (Roma)* 42, 237–243.
- Golding, J.P., Tsoni, S., Dixon, M., Yee, K.T., Partridge, T.A., Beauchamp, J.R., et al., 2004a. Heparin-binding EGF-like growth factor shows transient left–right asymmetrical expression in mouse myotome pairs. *Mech. Dev.* 2004; in press.
- Golding, J.P., Partridge, T.A., Beauchamp, J.R., King, T., Brown, N.A., Gassmann, M., Zammit, P.S., 2004b. Mouse myotomes exhibit left–right asymmetric expression of MLC3F and  $\alpha$ -skeletal actin. *Dev. Dyn.* 2004; in press.
- Goodenough, D.A., Goliger, J.A., Paul, D.L., 1996. Connexins, connexons, and intercellular communication. *Annu. Rev. Biochem.* 65, 475–502.
- Granata, A., Quaderi, N.A., 2003. The Opitz syndrome gene MID1 is essential for establishing asymmetric gene expression in Hensen's node. *Dev. Biol.* 258, 397–405.
- Greenaway, J., Fantel, A., Juchau, M., 1986. On the capacity of nitroheterocyclic compounds to elicit an unusual axial asymmetry in cultured rat embryos. *Toxicol. Appl. Pharmacol.* 82, 307–315.
- Guthrie, S., 1984. Patterns of junctional communication in the early amphibian embryo. *Nature* 311, 149–151.
- Guthrie, S., Gilula, N., 1989. Gap junctional communication and development. *Trends Neurosci.* 12, 12–16.
- Guthrie, S., Turin, L., Warner, A., 1988. Patterns of junctional communication during development of the early amphibian embryo. *Development* 103, 769–783.
- Halpern, M., Ho, R., Walker, C., Kimmel, C., 1993. Induction of muscle pioneers and floor plate is distinguished by the zebrafish no tail mutation. *Cell* 75, 99–111.
- Halpern, M.E., Liang, J.O., Gamse, J.T., 2003. Leaning to the left: laterality in the zebrafish forebrain. *Trends Neurosci.* 26, 308–313.
- Hamada, H., Meno, C., Watanabe, D., Saijoh, Y., 2002. Establishment of vertebrate left–right asymmetry. *Nat. Rev. Genet.* 3, 103–113.
- Happle, R., 2002. Dohi memorial lecture. New aspects of cutaneous mosaicism. *J. Dermatol.* 29, 681–692.
- Happle, R., Mittag, H., Kuster, W., 1995. The CHILD nevus: a distinct skin disorder. *Dermatology* 191, 210–216.
- Harland, R., Gerhart, J., 1997. Formation and function of Spemann's organizer. *Annu. Rev. of Cell Dev. Biol.* 13, 611–667.
- Harnad, S., 1977. Lateralization in the Nervous System. Academic Press, New York, p. 537.
- Harrison, C., Funnell, B., 1964. Relationship of paleomagnetic reversals and micropaleontology in two Cenozoic cores from the Pacific Ocean. *Nature* 204, 566.
- Hashimoto, H., Mizuta, A., Okada, N., Suzuki, T., Tagawa, M., Tabata, K., et al., 2002. Isolation and characterization of a Japanese flounder clonal line, reversed, which exhibits reversal of metamorphic left–right asymmetry. *Mech. Dev.* 111, 17–24.
- Hashimoto, H., Rebagliati, M., Ahmad, N., Muraoka, O., Kurokawa, T., Hibi, M., Suzuki, T., 2004. The Cerberus/Dan-family protein Charon is a negative regulator of Nodal signaling during left–right patterning in zebrafish. *Development* 131, 1741–1753.
- Hatcher, C.J., Goldstein, M.M., Mah, C.S., Delia, C.S., Basson, C.T., 2000. Identification and localization of TBX5 transcription factor during human cardiac morphogenesis. *Dev. Dyn.* 219, 90–95.
- Hayashi, T., Murakami, R., 2001. Left–right asymmetry in *Drosophila melanogaster* gut development. *Dev. Growth Differ.* 43, 239–246.
- Hermann, G.J., Leung, B., Priess, J.R., 2000. Left–right asymmetry in *C. elegans* intestine organogenesis involves a LIN-12/Notch signaling pathway. *Development* 127, 3429–3440.
- Hertwig, O., 1902. *Lehrbuch der Entwicklungsgeschichte des Menschen und der Wirbelthiere*. Aufl. Fischer, Jena 7.
- Heymer, J., Kuehn, M., Ruther, U., 1997a. The expression pattern of nodal and lefty in the mouse mutant Ft suggests a function in the establishment of handedness. *Mech. Dev.* 66, 5–11.
- Heymer, J., Kuehn, M., Ruther, U., 1997b. The expression pattern of nodal and lefty in the mouse mutant Ft suggests a function in the establishment of handedness. *Mech. Dev.* 66, 5–11.
- Horne-Badovinac, S., Rebagliati, M., Stainier, D.Y., 2003. A cellular framework for gut-looping morphogenesis in zebrafish. *Science* 302, 662–665.
- Hoshijima, K., Metherall, J.E., Grunwald, D.J., 2002. A protein disulfide isomerase expressed in the embryonic midline is required for left/right asymmetries. *Genes Dev.* 16, 2518–2529.
- Hoyle, C., Brown, N., Wolpert, L., 1992. Development of left/right handedness in the chick heart. *Development* 115, 1071–1078.
- Hutter, H., Schnabel, R., 1995. Establishment of left–right asymmetry in the *Caenorhabditis elegans* embryo: a multistep process involving a series of inductive events. *Development* 121, 3417–3424.
- Huxley, J., deBeer, G., 1963. *Elements of Experimental Embryology*. Hafner, New York.
- Hyatt, B., Yost, H., 1998. The left–right coordinator: the role of Vg1 in organizing left–right axis. *Cell* 93, 37–46.
- Hyatt, B., Lohr, J., Yost, H., 1996. Initiation of left–right axis formation by maternal Vg1. *Nature* 384, 62–65.
- Ibanez-Tallon, I., Gorokhova, S., Heintz, N., 2002. Loss of function of axonemal dynein Mdnah5 causes primary ciliary dyskinesia and hydrocephalus. *Hum. Mol. Genet.* 11, 715–721.
- Inouye, M., Murakami, U., 1978. Teratogenic effect of *N*-methyl-*N'*-nitro-*N*-nitrosoguanidine in mice. *Teratology* 18, 263–268.
- Isaac, A., Sargent, M.S., Cooke, J., 1997. Control of vertebrate left–right asymmetry by a snail-related zinc finger gene. *Science* 275, 1301.
- Itasaki, N., Nakamura, H., Yasuda, M., 1989. Changes in the arrangement of actin bundles during heart looping in the chick embryo. *Anat. Embryol (Berlin)* 180, 413–420.
- Itasaki, N., Nakamura, H., Sumida, H., Yasuda, M., 1991. Actin bundles on the right side in the caudal part of the heart tube play a role in dextro-looping in the embryonic chick heart. *Anat. Embryol.* 183, 29–39.
- Izraeli, S., Lowe, L., Bertness, V., Good, D., Dorward, D., Kirsch, I., Kuehn, M., 1999. The SIL gene is required for mouse embryonic axial development and left–right specification. *Nature* 399, 691–694.
- James, W., 1983. Twinning, handedness, and embryology. *Percept. Mot. Skills.* 56, 721–722.
- Jefferies, R., 1991. Two types of bilateral symmetry in the Metazoa: chordate and bilaterian. *Ciba Foundation Symposium* 162, 94–127.
- Jefferies, R.P.S., Brown, N.A., Daley, P.E.J., 1996. The early phylogeny of chordates and echinoderms and the origin of chordate left–right asymmetry and bilateral symmetry. *Acta Zoologica (Stockholm)* 77, 101–122.
- Johnson, M.H., 2001. Mammalian development: axes in the egg?. *Curr. Biol.* 11, R281–R284.
- Johnston, R.J., Hobert, O., 2003. A microRNA controlling left/right neuronal asymmetry in *Caenorhabditis elegans*. *Nature* 426, 845–849.
- Kapur, R., Jack, R., Siebert, J., 1994. Diamniotic placentation associated with omphalopagus conjoined twins. *Am. J. Med. Genet.* 52, 188–195.
- Kathiriya, I.S., Srivastava, D., 2000. Left–right asymmetry and cardiac looping: implications for cardiac development and congenital heart disease. *Am. J. Med. Genet.* 97, 271–279.



- Kawakami, M., Nakanishi, N., 2001. The role of an endogenous PKA inhibitor, PKI $\alpha$ , in organizing left–right axis formation. *Development Suppl.* 128, 2509–2515.
- Kelly, K., Wei, Y., Mikawa, T., 2002. Cell death along the embryo midline regulates left–right sidedness. *Dev. Dyn.* 224, 238–244.
- Kennedy, D., O’Craven, K., Ticho, B., Goldstein, A., Makris, N., Henson, J., 1999. Structural and functional brain asymmetries in human situs inversus totalis. *Neurology* 53, 1260–1265.
- Kilner, P.J., Yang, G.Z., Wilkes, A.J., Mohiaddin, R.H., Firmin, D.N., Yacoub, M.H., 2000. Asymmetric redirection of flow through the heart. *Nature* 404, 759–761.
- King, T., Beddington, R.S., Brown, N.A., 1998. The role of the brachyury gene in heart development and left–right specification in the mouse. *Mech. Dev.* 79, 29–37.
- Kitaguchi, T., Nagai, T., Nakata, K., Aruga, J., Mikoshiba, K., 2000. *Zic3* is involved in the left–right specification of the *Xenopus* embryo. *Development Suppl.* 127, 4787–4795.
- Klingenberg, C.P., McIntyre, G.S., Zaklan, S.D., 1998. Left–right asymmetry of fly wings and the evolution of body axes. [erratum appears in *Proc. R. Soc. Lond. B. Biol. Sci.* 1998 Dec 22;265(1413):2455.] *Proc. R. Soc. Lond. Ser. B: Biol. Sci.* 265, 1255–1259.
- Kloppel, R., Rothe, K., Hoermann, D., Schmidt, F., Bennek, J., Kahn, T., 2002. Proteus syndrome. *J. Comput. Assis. Tomogr.* 26, 262–265.
- Kobayashi, Y., Watanabe, M., Okada, Y., Sawa, H., Takai, H., Nakanishi, M., et al., 2002. Hydrocephalus, situs inversus, chronic sinusitis, and male infertility in DNA polymerase lambda-deficient mice: possible implication for the pathogenesis of immotile cilia syndrome. *Mol. Cell. Biol.* 22, 2769–2776.
- Kölliker, A., 1879. *Entwicklungsgeschichte des Menschen und höheren Thiere.* Wilhelm Engelmann, Leipzig.
- Konig, A., Happle, R., Bornholdt, D., Engel, H., Grzeschik, K.H., 2000. Mutations in the NSDHL gene, encoding a 3 $\beta$ -hydroxysteroid dehydrogenase, cause CHILD syndrome. *Am. J. Med. Genet.* 90, 339–346.
- Korzth, S., Emelyanov, A., Korzh, V., 2001. Developmental analysis of ceruloplasmin gene and liver formation in zebrafish. *Mech. Dev.* 103, 137–139.
- Kosaki, K., Casey, B., 1998. Genetics of human left–right axis malformations. *Sem. Cell Dev. Biol.* 9, 89–99.
- Kramer, K.L., Yost, H.J., 2002. Ectodermal syndecan-2 mediates left–right axis formation in migrating mesoderm as a cell-nonautonomous Vg1 cofactor. *Developmental Cell* 2, 115–124.
- Kramer, K.L., Barnette, J.E., Yost, H.J., 2002. PKC $\gamma$  regulates syndecan-2 inside-out signaling during *xenopus* left–right development. *Cell* 111, 981–990.
- Krebs, L.T., Iwai, N., Nonaka, S., Welsh, I.C., Lan, Y., Jiang, R., et al., 2003. Notch signaling regulates left–right asymmetry determination by inducing Nodal expression. *Genes Dev.* 17, 1207–1212.
- Krob, G., Braun, A., Kuhnle, U., 1994. True hermaphroditism: geographical distribution, clinical findings, chromosomes and gonadal histology. *Eur. J. Pediatr.* 153, 2–10.
- Landesman, Y., Goodenough, D.A., Paul, D.L., 2000. Gap junctional communication in the early *Xenopus* embryo. *J. Cell Biol.* 150, 929–936.
- Lauterbach, C.E., 1925. Studies in twin resemblance. *Genetics* 10, 525–568.
- Layton, W., Hallesy, D., 1965. Forelimb deformity in rats: association with acetazolamide. *Science* 196(5), 149.
- Layton, W., Layton, M., 1979. Cadmium induced limb defects in mice. *Teratology* 19, 229–236.
- Leung, A.K., Fong, J.H., Leong, A.G., 2002. Hemihypertrophy. *J. R. Soc. Health* 122, 24–27.
- Levin, M., 1995. The evolution of understanding: a genetic algorithm model of the evolution of communication. *Biosystems* 36, 167–178.
- Levin, M., 1996. *Molecular Basis of Left–Right Asymmetry in Chick Development.* Harvard University Press, Boston, MA.
- Levin, M., 1998a. Follistatin mimics the endogenous streak inhibitory activity in early chick embryos. *Int. J. Dev. Biol.* 42, 553–559.
- Levin, M., 1998b. Left–Right asymmetry and the chick embryo. *Sem. Cell Dev. Biol.* 9, 67–76.
- Levin, M., 1998c. Left–right asymmetry and the chick embryo. *Sem. Cell Dev. Biol.* 9, 67–76.
- Levin, M., 1998d. The roles of activin and follistatin signaling in chick gastrulation. *Int. J. Dev. Biol.* 42, 553–559.
- Levin, M., 2001. Isolation and community: the role of gap junctional communication in embryonic patterning. *J. Membr. Biol.* 185, 177–192.
- Levin, M., 2003a. Electric embryos: endogenous ion fluxes and voltage gradients in left–right asymmetry. *Dev. Biol.* 259, 482.
- Levin, M., 2003b. Hypothesis: motor proteins and ion pumps, not ciliary motion, initiate LR asymmetry. *BioEssays* 25, 1002–1010.
- Levin, M., 2004a. Embryonic origins of left–right asymmetry. *Crit. Rev. Oral Biol Med.* 15 (4), 197–206.
- Levin, M., 2004b. Left–right asymmetry in amphibian embryogenesis. in: Heatwole, H., Brizuela, B. (Eds.), *Biology of the Amphibia*, vol. 6. Surrey Beatty & Sons, Australia, in press.
- Levin, M., Mercola, M., 1998a. The compulsion of chirality. *Genes Dev.* 12, 763–769.
- Levin, M., Mercola, M., 1998b. The compulsion of chirality: toward an understanding of left–right asymmetry. *Genes Dev.* 12, 763–769.
- Levin, M., Mercola, M., 1998c. Gap junctions are involved in the early generation of left right asymmetry. *Dev. Biol.* 203, 90–105.
- Levin, M., Mercola, M., 1999. Gap junction-mediated transfer of left–right patterning signals in the early chick blastoderm is upstream of Shh asymmetry in the node. *Development* 126, 4703–4714.
- Levin, M., Nascone, N., 1997. Two molecular models of initial left–right asymmetry generation. *Med. Hypoth.* 49, 429–435.
- Levin, M., Johnson, R., Stern, C., Kuehn, M., Tabin, C., 1995. A molecular pathway determining left–right asymmetry in chick embryogenesis. *Cell* 82, 803–814.
- Levin, M., Roberts, D., Holmes, L., Tabin, C., 1996. Laterality defects in conjoined twins. *Nature* 384, 321.
- Levin, M., Pagan, S., Roberts, D., Cooke, J., Kuehn, M., Tabin, C., 1997a. Left/right patterning signals and the independent regulation of different aspects of situs in the chick embryo. *Dev. Biol.* 189, 57–67.
- Levin, M., Pagan, S., Roberts, D.J., Cooke, J., Kuehn, M.R., Tabin, C.J., 1997b. Left/right patterning signals and the independent regulation of different aspects of Situs in the chick embryo. *Dev. Biol.* 189, 57–67.
- Levin, M., Thorlin, T., Robinson, K., Nogi, T., Mercola, M., 2002. Asymmetries in H $^{+}$ /K $^{+}$ -ATPase and cell membrane potentials comprise a very early step in left–right patterning. *Cell* 111, 77–89.
- Lewin, S.O., Opitz, J.M., 1986. Fibular a/hypoplasia: review and documentation of the fibular developmental field. *Am. J. Med. Genet. Suppl.* 2, 215–238.
- Liang, J.O., Etheridge, A., Hantsoo, L., Rubinstein, A.L., Nowak, S.J., Izpisua Belmonte, J.C., Halpern, M.E., 2000. Asymmetric nodal signaling in the zebrafish diencephalon positions the pineal organ. *Development* 127, 5101–5112.
- Ligoxygakis, P., Strigini, M., Averof, M., 2001. Specification of left–right asymmetry in the embryonic gut of *Drosophila*. *Development Suppl.* 128, 1171–1174.
- Linask, K.K., Han, M.D., Artman, M., Ludwig, C.A., 2001. Sodium–calcium exchanger (NCX-1) and calcium modulation: NCX protein expression patterns and regulation of early heart development. *Dev. Dyn.* 221, 249–264.
- Liu, X.Y., Dangel, A.W., Kelley, R.I., Zhao, W., Denny, P., Botcherby, M., et al., 1999. The gene mutated in bare patches and striated mice encodes a novel 3 $\beta$ -hydroxysteroid dehydrogenase. *Nat. Genet.* 22, 182–187.
- Lo, C.W., 1996. The role of gap junction membrane channels in development. *J. Bioenerget. Biomembr.* 28, 379–385.
- Logan, M., Pagan-Westphal, S., Smith, D., Paganessi, L., Tabin, C., 1998. The transcription factor Pitx2 mediates situs-specific morphogenesis in response to left–right asymmetric signals. *Cell* 94, 307–317.

- Lohr, J., Danos, M., Yost, H., 1997a. Left–right asymmetry of a nodal-related gene is regulated by dorsoanterior midline structures during *Xenopus* development. *Development* 124, 1465–1472.
- Lohr, J.L., Danos, M.C., Yost, H.J., 1997b. Left–right asymmetry of a nodal-related gene is regulated by dorsoanterior midline structures during *Xenopus* development. *Development Suppl.* 124, 1465–1472.
- Long, S., Ahmad, N., Rebagliati, M., 2003. The zebrafish nodal-related gene southpaw is required for visceral and diencephalic left–right asymmetry. *Development* 130, 2303–2316.
- Lowe, L., Supp, D., Sampath, K., Yokoyama, T., Wright, C., Potter, S., et al., 1996a. Conserved left–right asymmetry of nodal expression and alterations in murine situs inversus. *Nature* 381, 158–161.
- Lowe, L.A., Supp, D.M., Sampath, K., Yokoyama, T., Wright, C.V., Potter, S.S., et al., 1996b. Conserved left–right asymmetry of nodal expression and alterations in murine situs inversus. *Nature* 381, 158–161.
- Manasek, F., 1981. Determinants of heart shape in early embryos. *Federation Proc.* 40, 2011–2016.
- Manner, J., 2004. On rotation, torsion, lateralization, and handedness of the embryonic heart loop: new insights from a simulation model for the heart loop of chick embryos. *The Anatomical Record* 278A, 481–492.
- Marszalek, J.R., Ruiz-Lozano, P., Roberts, E., Chien, K.R., Goldstein, L.S., 1999. Situs inversus and embryonic ciliary morphogenesis defects in mouse mutants lacking the KIF3A subunit of kinesin-II. *Proc. Natl. Acad. Sci. USA* 96, 5043–5048.
- Martin-Blanco, E., Garcia-Bellido, A., 1996. Mutations in the rotated abdomen locus affect muscle development and reveal an intrinsic asymmetry in *Drosophila*. *Proc. Natl. Acad. Sci. USA* 93, 6048–6052.
- Matsumoto, J., Seikai, T., 1992. Asymmetric pigmentation and pigment disorders in pleuronectiformes (flounders). *Pigment Cell Res. Suppl.* 2, 275–282.
- McCain, E., McClay, D., 1994. The establishment of bilateral asymmetry in sea urchin embryos. *Development* 120, 395–404.
- McCarthy, A., 1990. *Teratology* 42, 33A.
- McGrath, J., Brueckner, M., 2003. Cilia are at the heart of vertebrate left–right asymmetry. *Curr. Opin. Genet. Dev.* 13, 385–392.
- McGrath, J., Somlo, S., Makova, S., Tian, X., Brueckner, M., 2003. Two populations of node monocilia initiate left–right asymmetry in the mouse. *Cell* 114, 61–73.
- McManus, I.C., 1995. Familial sinistrality: the utility of calculating exact genotype probabilities for individuals. *Cortex* 31, 3–24.
- McManus, I.C., Bryden, M.P., 1992. The genetics of handedness, cerebral dominance, and lateralization. In: Rapin, I., Segalowitz, S. (Eds.), *Handbook of Neuropsychology*, vol. 6(10). Elsevier, Amsterdam, pp. 115–144.
- McManus, I.C., Martin, N., Stubbings, G., Chung, E.M.K., Mitchison, H.M., 2004. Handedness and situs inversus in primary ciliary dyskinesia. *Proc. R. Soc. Lond. Ser. B: Biol. Sci.* 2004; in press.
- McMurrich, J., 1894. *A Textbook of Invertebrate Morphology*. Holt, New York.
- Meinhardt, H., 2002. The radial-symmetric hydra and the evolution of the bilateral body plan: an old body became a young brain. *Bioessays* 24, 185–191.
- Meinhardt, H., Gierer, A., 2000. Pattern formation by local self-activation and lateral inhibition. *Bioessays* 22, 753–760.
- Melloy, P., Ewart, J., Cohen, M., Desmond, M., Kuehn, M., Lo, C., 1998. No turning, a mouse mutation causing left–right and axial patterning defects. *Dev. Biol.* 193, 77–89.
- Meno, C., Saijoh, Y., Fujii, H., Ikeda, M., Yokoyama, T., Yokoyama, M., et al., 1996. Left–right asymmetric expression of the TGF $\beta$ -family member *lefty* in mouse embryos. *Nature* 381, 151–155.
- Meno, C., Shimono, A., Saijoh, Y., Yashiro, K., Mochida, K., Ohishi, S., et al., 1998. *Lefty-1* is required for left–right determination as a regulator of *lefty-2* and nodal. *Cell* 94, 287–297.
- Meno, C., Gritsman, K., Ohishi, S., Ohfuji, Y., Heckscher, E., Mochida, K., et al., 1999. Mouse *Lefty2* and zebrafish *antivin* are feedback inhibitors of nodal signaling during vertebrate gastrulation. *Mol. Cell* 4, 287–298.
- Mensing, C.A., 1983. Mirror-image twins. *Northwest Dent* 62, 41–42.
- Mercola, M., 2003. Left–right asymmetry: nodal points. *J. Cell Sci.* 116, 3251–3257.
- Mercola, M., Levin, M., 2001. Left–right asymmetry determination in vertebrates. *Ann. Rev. Cell. Dev. Biol.* 17, 779–805.
- Meyers, E.N., Martin, G.R., 1999. Differences in left–right axis pathways in mouse and chick: functions of FGF8 and SHH. *Science* 285, 403–406.
- Miklosi, A., Andrew, R.J., 1999. Right eye use associated with decision to bite in zebrafish. *Behav. Brain. Res.* 105, 199–205.
- Milaire, J., 1985. Histological changes induced in developing limb buds of C57BL mouse embryos submitted in utero to the combined influence of acetazolamide and cadmium sulfate. *Teratology* 32, 433–451.
- Minguillon, C., Garcia-Fernandez, J., 2002. The single amphioxus *Mox* gene: insights into the functional evolution of *Mox* genes, somites, and the asymmetry of amphioxus somitogenesis. *Dev. Biol.* 246, 455–465.
- Mittwoch, U., 2000. Genetics of sex determination: exceptions that prove the rule. *Mol. Genet. Metab.* 71, 405–410.
- Mochizuki, T., Saijoh, Y., Tsuchiya, K., Shirayoshi, Y., Takai, S., Taya, C., et al., 1998. Cloning of *inv*, a gene that controls left/right asymmetry and kidney development. *Nature* 395, 177–181.
- Monsoro-Burq, A., LeDouarin, N., 2000. Left–right asymmetry in BMP4 signalling pathway during chick gastrulation. *Mech. Dev.* 97, 105–108.
- Morgan, D., Turnpenny, L., Goodship, J., Dai, W., Majumder, K., Matthews, L., et al., 1998. *Inversin*, a novel gene in the vertebrate left–right axis pathway, is partially deleted in the *inv* mouse. *Nat. Genet.* 20, 149–156.
- Morgan, D., Goodship, J., Essner, J.J., Vogan, K.J., Turnpenny, L., Yost, H.J., et al., 2002. The left–right determinant *inversin* has highly conserved ankyrin repeat and IQ domains and interacts with calmodulin. *Human Genetics* 110, 377–384.
- Morini, F., Ilari, M., Casati, A., Pisera, A., Oriolo, L., Cozzi, D.A., 2002. Posterior urethral valves and mirror image anomalies in monozygotic twins. *Am. J. Med. Genet.* 111, 210–212.
- Morison, D., Reyes, C.V., Skorodin, M.S., 1994. Mirror-image tumors in mirror-image twins. *Chest* 106, 608–610.
- Morokuma, J., Ueno, M., Kawanishi, H., Saiga, H., Nishida, H., 2002. *HrNodal*, the ascidian nodal-related gene, is expressed in the left side of the epidermis, and lies upstream of *HrPitx*. *Dev. Genes. Evol.* 212, 439–446.
- Morrill, C., 1919. Symmetry reversal and mirror imaging in monstrous trout and a comparison with similar conditions in human double monsters. *Anat. Record* 16, 265–292.
- Muller, J.K., Prather, D.R., Nascone-Yoder, N.M., 2003. Left–right asymmetric morphogenesis in the *Xenopus* digestive system. *Dev. Dyn.* 228, 672–682.
- Murcia, N.S., Richards, W.G., Yoder, B.K., Mucenski, M.L., Dunlap, J.R., Woychik, R.P., 2000. The oak ridge polycystic kidney (*orpk*) disease gene is required for left–right axis determination. *Development* 127, 2347–2355.
- Murray, J., Clarke, B., 1966. The inheritance of polymorphic shell characters in *Partula* (Gastropoda). *Genetics* 54, 1261–1277.
- Nascone, N., Mercola, M., 1997. Organizer induction determines left–right asymmetry in *Xenopus*. *Dev. Biol.* 189, 68–78.
- Nelsen, E., Frankel, J., Jenkins, L., 1989. Non-genic inheritance of cellular handedness. *Development* 105, 447–456.
- Neville, A., 1976. *Animal Asymmetry*. Edward Arnold, London.
- Newbury-Ecob, R.A., Leanage, R., Raeburn, J.A., Young, I.D., 1996. Holt–Oram syndrome: A clinical genetic study. *J. Med. Genet.* 33, 300–307.
- Newman, H., 1916. Heredity and organic symmetry in armadillo quadruplets. *Biol. Bull.* XXX, 173–203.
- Newman, H., Freeman, F., Holzinger, K., 1937. *Twins: A Study of Heredity and Environment*. University of Chicago Press, Chicago.
- Newman, C., Grow, M., Cleaver, O., Chia, F., Krieg, P., 1997. *Xbap*, a vertebrate gene related to *bagpipe*, is expressed in developing craniofacial structures and in anterior gut muscle. *Dev. Biol.* 181, 223–233.
- Nonaka, S., Tanaka, Y., Okada, Y., Takeda, S., Harada, A., Kanai, Y., et al., 1998. Randomization of left–right asymmetry due to loss of nodal cilia generating leftward flow of extraembryonic fluid in mice lacking KIF3B motor protein. *Cell* 95, 829–837.

- Oh, S., Li, E., 1997. The signaling pathway mediated by the type IIB activin receptor controls axial patterning and lateral asymmetry in the mouse. *Genes Dev.* 11, 1812–1826.
- Okada, Y., Nonaka, S., Tanaka, Y., Saijoh, Y., Hamada, H., Hirokawa, N., 1999. Abnormal nodal flow precedes situs inversus in iv and inv mice. *Mol. Cell* 4, 459–468.
- Okada, N., Takagi, Y., Seikai, T., Tanaka, M., Tagawa, M., 2001a. Asymmetrical development of bones and soft tissues during eye migration of metamorphosing Japanese flounder, *Paralichthys olivaceus*. *Cell Tissue Res.* 304, 59–66.
- Okada, N., Takagi, Y., Seikai, T., Tanaka, M., Tagawa, M., 2001b. Asymmetrical development of bones and soft tissues during eye migration of metamorphosing Japanese flounder, *Paralichthys olivaceus*. *Cell Tissue Res.* 304, 59–66.
- Okamoto, F., Nonoyama, T., Hommura, S., 2001. Mirror image myopic anisometropia in two pairs of monozygotic twins. *Ophthalmologica* 215, 435–438.
- Olbrich, H., Haffner, K., Kispert, A., Volkel, A., Volz, A., Sasmaz, G., et al., 2002. Mutations in DNAH5 cause primary ciliary dyskinesia and randomization of left–right asymmetry. *Nat. Genet.* 30, 143–144.
- Olson, D.J., Christian, J.L., Moon, R.T., 1991. Effect of wnt-1 and related proteins on gap junctional communication in *Xenopus* embryos. *Science* 252, 1173–1176.
- Opitz, J.M., Utkus, A., 2001. Comments on biological asymmetry. *Am. J. Med. Genet.* 101, 359–369.
- Otto, E.A., Schermer, B., Obara, T., O’Toole, J.F., Hiller, K.S., Mueller, A.M., et al., 2003. Mutations in INVS encoding inversin cause nephronophthisis type 2, linking renal cystic disease to the function of primary cilia and left–right axis determination. [comment]. *Nat. Genet.* 34, 413–420.
- Pagan-Westphal, S., Tabin, C., 1998. The transfer of left–right positional information during chick embryogenesis. *Cell* 93, 25–35.
- Paulozzi, L.J., Lary, J.M., 1999. Laterality patterns in infants with external birth defects. *Teratology* 60, 265–271.
- Peeters, H., Debeer, P., Bairoch, A., Wilquet, V., Huysmans, C., Parthoens, E., et al., 2003. PA26 is a candidate gene for heterotaxia in humans: identification of a novel PA26-related gene family in human and mouse. *Human Genet.* 112, 573–580.
- Pennekamp, P., Karcher, C., Fischer, A., Schweickert, A., Skryabin, B., Horst, J., et al., 2002. The ion channel polycystin-2 is required for left–right axis determination in mice. *Curr. Biol.* 12, 938–943.
- Phillips, R.J., Hawker, S.G., Moseley, H.J., 1973. Bare-patches, a new sex-linked gene in the mouse, associated with a high production of XO females. I. A preliminary report of breeding experiments. *Genet. Res.* 22, 91–99.
- Potter, R.H., Nance, W.E., 1976. A twin study of dental dimension. I. Discordance, asymmetry, and mirror imagery. *Am. J. Phys. Anthropol.* 44, 391–395.
- Przemeck, G.K., Heinzmann, U., Beckers, J., Hrabe de Angelis, M., 2003. Node and midline defects are associated with left–right development in Delta1 mutant embryos. *Development* 130, 3–13.
- Psychoyos, D., Stern, C., 1996. Restoration of the organizer after radical ablation of Hensen’s node and the anterior primitive streak in the chick embryo. *Development* 122, 3263–3273.
- Purandare, S.M., Ware, S.M., Kwan, K.M., Gebbia, M., Bassi, M.T., Deng, J.M., et al., 2002. A complex syndrome of left–right axis, central nervous system and axial skeleton defects in Zic3 mutant mice. *Development* 129, 2293–2302.
- Ramsdell, A.F., Yost, H.J., 1999. Cardiac looping and the vertebrate left–right axis: antagonism of left-sided Vg1 activity by a right-sided ALK2-dependent BMP pathway. *Development* 126, 5195–5205.
- Rankin, C.T., Bunton, T., Lawler, A.M., Lee, S.J., 2000. Regulation of left–right patterning in mice by growth/differentiation factor-1. *Nat. Genet.* 24, 262–265.
- Rasskin-Gutman, D., Izpisua-Belmonte, J.C., 2004. Theoretical morphology of developmental asymmetries. *Bioessays* 26, 405–412.
- Raya, A., Kawakami, Y., Rodriguez-Esteban, C., Buscher, D., Koth, C.M., Itoh, T., et al., 2003a. Notch activity induces Nodal expression and mediates the establishment of left–right asymmetry in vertebrate embryos. *Genes Dev.* 17, 1213–1218.
- Raya, A., Kawakami, Y., Rodriguez-Esteban, C., Buscher, D., Koth, C.M., Itoh, T., et al., 2003b. Notch activity induces Nodal expression and mediates the establishment of left–right asymmetry in vertebrate embryos. *Genes Dev.* 17, 1213–1218.
- Raya, A., Kawakami, Y., Rodriguez-Esteban, C., Ibanes, M., Rasskin-Gutman, D., Rodriguez-Leon, J., et al., 2004. Notch activity acts as a sensor for extracellular calcium during vertebrate left–right determination. *Nature* 427, 121–128.
- Richieri-Costa, A., Opitz, J.M., 1986. Ulnar ray a/hypoplasia: evidence for a developmental field defect on the basis of genetic heterogeneity. Report of three Brazilian families. *Am. J. Med. Genet. Suppl.* 2, 195–206.
- Rife, D.C., 1933. Genetic studies of monozygotic twins, III: mirror-imaging. *J. Heredity* 24, 443–446.
- Rife, D.C., 1940. Handedness, with special reference to twins. *Genetics* 25, 178–186.
- Rife, D.C., 1980. Laterality differences in twins. *Behav. Brain Sci.* 3, 477–478.
- Robinson, S.R., Hampson, E.C., Munro, M.N., Vaney, D.I., 1993. Unidirectional coupling of gap junctions between neuroglia. *Science* 262, 1072–1074.
- Rodriguez-Esteban, C., Capdevila, J., Kawakami, Y., Izpisua Belmonte, J.C., 2001. Wnt signaling and PKA control Nodal expression and left–right determination in the chick embryo. *Development Suppl.* 128, 3189–3195.
- Roebroek, A.J., Umans, L., Pauli, I.G., Robertson, E.J., Van Leuven, F., Van De Ven, W.J., Constam, D.B., 1998. Failure of ventral closure and axial rotation in embryos lacking the proprotein convertase Furin. *Development* 125, 4863–4876.
- Romer, A., 1962. *The Invertebrate Body*. Saunders, London.
- Ryan, A., Blumberg, B., Rodriguez-Esteban, C., Yonei-Tamura, S., Tamura, K., Tsukui, T., et al., 1998. Pitx2 determines left–right asymmetry of internal organs in vertebrates. *Nature* 394, 545–551.
- Sampath, K., Cheng, A.M., Frisch, A., Wright, C.V., 1997. Functional differences among *Xenopus* nodal-related genes in left–right axis determination. *Development* 124, 3293–3302.
- Sarkar, S., Prakash, D., Marwaha, R.K., Samujh, R., Rao, K.L., 1992. Congenital hemihypertrophy and Wilms’ tumor. *Indian Pediatr.* 29, 1160–1162.
- Satoh, K., Shibata, Y., Tokushige, H., Onizuka, T., 1995. A mirror image of the first and second branchial arch syndrome associated with cleft lip and palate in monozygotic twins. *Br. J. Plas. Surg.* 48, 601–605.
- Schier, A.F., Shen, M.M., 2000. Nodal signalling in vertebrate development. *Nature* 403, 385–389.
- Schilling, T., Concordet, J., Ingham, P., 1999. Regulation of left–right asymmetries in the zebrafish by Shh and BMP4. *Dev. Biol.* 210, 277–287.
- Schneider, P.E., 1985. Mirror-image twins with geminated incisors. Report of a case. *Quintessence Intl.* 16, 429–431.
- Schneider, A., Mijalski, T., Schlange, T., Dai, W., Overbeek, P., Arnold, H., Brand, T., 1999. The homeobox gene NKX3.2 is a target of left–right signalling and is expressed on opposite sides in chick and mouse embryos. *Curr. Biol.* 9, 911–914.
- Schreiner, C.M., Scott Jr., W.J., Supp, D.M., Potter, S.S., 1993. Correlation of forelimb malformation asymmetries with visceral organ situs in the transgenic mouse insertional mutation, legless. *Dev. Biol.* 158, 560–562.
- Shenefelt, R., 1972. Morphogenesis of malformations in hamsters caused by retinoic acid. *Teratology* 5, 103–118.
- Shimeld, S., 1999. The evolution of the hedgehog gene family in chordates: insights from amphioxus hedgehog. *Dev. Genes. Evol.* 209, 40–47.

- Shimeld, S.M., 2003. in: Lemaire, P. (Ed.), Regulation of Left Right Asymmetry in Ciona. International Urochordate Meeting Carry le Rouet, France.
- Singh, G., Supp, D., Schreiner, C., McNeish, J., Merker, H., Copeland, N., et al., 1991. Legless insertional mutation: morphological, molecular, and genetic characterization. *Genes Dev.* 5, 2245–2255.
- Smith, A.T., Sack Jr., G.H., Taylor, G.J., 1979. Holt-Oram syndrome. *J. Pediatr.* 95, 538–543.
- Smith, S., Dickman, E., Thompson, R., Sinning, A., Wunsch, A., Markwald, R., 1997. Retinoic acid directs cardiac laterality and the expression of early markers of precardiac asymmetry. *Dev. Biol.* 182, 162–171.
- Sommer, I., Ramsey, N., Bouma, A., Kahn, R., 1999. Cerebral mirror-imaging in a monozygotic twin. *Lancet* 354, 1445–1446.
- Sommer, I.E., Ramsey, N.F., Mandl, R.C., Kahn, R.S., 2002. Language lateralization in monozygotic twin pairs concordant and discordant for handedness. *Brain* 125, 2710–2718.
- Sparrow, D.B., Kotecha, S., Towers, N., Mohun, T.J., 1998. *Xenopus* eHAND: a marker for the developing cardiovascular system of the embryo that is regulated by bone morphogenetic proteins. *Mech. Dev.* 71, 151–163.
- Spemann, H., Falkenberg, H., 1919. Über Asymmetrische Entwicklung und Situs inversus viscerum bei Zwillingen und Doppelbildungen. *Wilhelm Roux' Archives Entwicklungsmechanik Organismen* 45, 371–422.
- Sperber, G.H., Machin, G.A., Bamforth, F.J., 1994. Mirror-image dental fusion and discordance in monozygotic twins. *Am. J. Med. Genet.* 51, 41–45.
- Springer, S.P., Searleman, A., 1978a. Hemispheric asymmetry of function in twins. *Prog. Clin. Biol. Res.* 24A, 57–62.
- Springer, S.P., Searleman, A., 1978b. Laterality in twins: the relationship between handedness and hemispheric asymmetry for speech. *Behav. Genet.* 8, 349–357.
- Srivastava, D., 1995. A subclass of bHLH proteins required for cardiac morphogenesis. *Science* 270, 1995–1999.
- Stalens, J.P., Maton, P., Gosseye, S., Clapuyt, P., Ninane, J., 1993. Hemihypertrophy, bilateral Wilms' tumor, and clear-cell adenocarcinoma of the uterine cervix in a young girl. *Med. Pediatr. Oncol.* 21, 671–675.
- Stalsberg, H., 1969a. The origin of heart asymmetry: right and left contributions to the early chick embryo heart. *Dev. Biol.* 19, 109–127.
- Stalsberg, H., 1969b. Regional mitotic activity in the precardiac mesoderm and differentiating heart tube in the chick embryo. *Dev. Biol.* 20, 18–45.
- Stolow, M.A., Shi, Y.B., 1995. *Xenopus* sonic hedgehog as a potential morphogen during embryogenesis and thyroid hormone-dependent metamorphosis. *Nucl. Acids. Res.* 23, 2555–2562.
- Streit, A., Thery, C., Stern, C., 1994. Of mice and frogs. *Trends Genet.* 10, 181–183.
- Streit, A., Stern, C.D., Thery, C., Ireland, G.W., Aparicio, S., Sharpe, M.J., Gherardi, E., 1995. A role for HGF/SF in neural induction and its expression in Hensen's node during gastrulation. *Development* 121, 813–824.
- Sulik, K., Dehart, D.B., Iangaki, T., Carson, J.L., Vrablic, T., Gesteland, K., Schoenwolf, G.C., 1994. Morphogenesis of the murine node and notochordal plate. *Dev. Dyn.* 201, 260–278.
- Sunderman Jr., F.W., Plowman, M.C., Hopfer, S.M., 1991. Embryotoxicity and teratogenicity of cadmium chloride in *Xenopus laevis*, assayed by the FETAX procedure. *Ann. Clin. Lab. Sci.* 21, 381–391.
- Sunderman Jr., F.W., Plowman, M.C., Hopfer, S.M., 1992. Teratogenicity of cadmium chloride in the South African frog, *Xenopus laevis*. *IARC. Sci. Publ.* 1992, 249–256.
- Supp, D.M., Witte, D.P., Potter, S.S., Brueckner, M., 1997. Mutation of an axonemal dynein affects left–right asymmetry in *inversus viscerum* mice. *Nature* 389, 963–966.
- Supp, D.M., Brueckner, M., Kuehn, M.R., Witte, D.P., Lowe, L.A., McGrath, J., et al., 1999. Targeted deletion of the ATP binding domain of left–right dynein confirms its role in specifying development of left–right asymmetries. *Development* 126, 5495–5504.
- Supp, D., Potter, S., Brueckner, M., 2000. Molecular motors: the driving force behind mammalian left–right development. *Trends Cell Biol.* 10, 41–45.
- Tabin, C.J., Vogan, K.J., 2003. A two-cilia model for vertebrate left–right axis specification. *Genes Dev.* 17, 1–6.
- Takeda, S., Yonekawa, Y., Tanaka, Y., Nonaka, Y.O.S., Hirokawa, N., 1999a. Left–right asymmetry and kinesin superfamily protein KIF3A. *J. Cell Biol.* 145, 825–836.
- Takeda, S., Yonekawa, Y., Tanaka, Y., Okada, Y., Nonaka, S., Hirokawa, N., 1999b. Left–right asymmetry and kinesin superfamily protein KIF3A: new insights in determination of laterality and mesoderm induction by *kif3A*  $-/-$  mice analysis. *J. Cell Biol.* 145, 825–836.
- Takeuchi, J.K., Ohgi, M., Koshihara-Takeuchi, K., Shiratori, H., Sakaki, I., Ogura, K., et al., 2003. *Tbx5* specifies the left/right ventricles and ventricular septum position during cardiogenesis. *Development* 130, 5953–5964.
- Talbot, W., Trevarrow, B., Halpern, M., Melby, A., Farr, G., Postlethwait, J., et al., 1995. A homeobox gene essential for zebrafish notochord development. *Nature* 378, 150–157.
- Tanaka, S., Kanzaki, R., Yoshibayashi, M., Kamiya, T., Sugishita, M., 1999. Dichotic listening in patients with situs inversus: brain asymmetry and situs asymmetry. *Neuropsychologia* 37, 869–874.
- Taulman, P.D., Haycraft, C.J., Balkovetz, D.F., Yoder, B.K., 2001. *Polaris*, a protein involved in left–right axis patterning, localizes to basal bodies and cilia. *Mol. Biol. Cell* 12, 589–599.
- Teel, A.L., Yost, H.J., 1996. Embryonic expression patterns of *Xenopus* syndecans. *Mech. Dev.* 59, 115–127.
- Terazawa, K., Satoh, N., 1995. Spatial expression of the amphioxus homologue of *Brachyury* (*T*) gene during early embryogenesis of *Branchiostoma belcheri*. *Dev. Growth. Diff.* 37, 395–401.
- Terazawa, K., Satoh, N., 1997. Formation of the chordamesoderm in the amphioxus embryo—analysis with *Brachyury* and *Fork head/Hnf-3* genes. *Dev. Genes. Evol.* 207, 1–11.
- Theissen, G., 2000. Evolutionary developmental genetics of floral symmetry: the revealing power of Linnaeus' monstrous flower. *Bioessays* 22, 209–213.
- Thickett, C., Morgan, R., 2002. *Hoxc-8* expression shows left–right asymmetry in the posterior lateral plate mesoderm. *Gene Expr. Patterns* 2, 5–6.
- Torgersen, J., 1950. Situs inversus, asymmetry and twinning. *American J. Human Genet.* 2, 361–370.
- Townsend, G., Richards, L., 1990. Twins and twinning, dentists and dentistry. *Aust. Dental J.* 35, 317–327.
- Toyoizumi, R., Kobayashi, T., Kikukawa, A., Oba, J., Takeuchi, S., 1997. Adrenergic neurotransmitters and calcium ionophore-induced situs inversus viscerum in *Xenopus laevis* embryos. *Dev. Growth Diff.* 39, 505–514.
- Tsuda, T., Philp, N., Zile, M.H., Linask, K.K., 1996. Left–right asymmetric localization of flectin in the extracellular matrix during heart looping. *Dev. Biol.* 173, 39–50.
- Tsukui, T., Capdevila, J., Tamura, K., Ruiz-Lozano, P., Rodriguez-Esteban, C., Yonei-Tamura, S., et al., 1999a. Multiple left–right asymmetry defects in *Shh*  $-/-$  mutant mice unveil a convergence of the *Shh* and retinoic acid pathways in the control of Lefty-1. *Proc. Natl. Acad. USA.* 96, 11381–11381.
- Tsukui, T., Capdevila, J., Tamura, K., Ruiz-Lozano, P., Rodriguez-Esteban, C., Yonei-Tamura, S., et al., 1999b. Multiple left–right asymmetry defects in *Shh*  $(-/-)$  mutant mice unveil a convergence of the *shh* and retinoic acid pathways in the control of Lefty-1. *Proc. Natl. Acad. Sci. USA* 96, 11376–11381.
- Tuinstra, E., DeJong, G., Scharloo, W., 1990. Lack of response to family selection for directional asymmetry in *Drosophila melanogaster*. *Proc. R. Soc. Lond. S. B* 241, 146–152.
- van Niekerk, W.A., Retief, A.E., 1981. The gonads of human true hermaphrodites. *Human Genet.* 58, 117–122.

- Viebahn, C., 2001. Hensen's node. *Genesis* 29, 96–103.
- Viebahn, C., Mayer, B., Miething, A., 1995. Morphology of incipient mesoderm formation in the rabbit embryo: a light- and retrospective electron-microscopic study. *Acta Anatomica (Basel)* 154, 99–110.
- Vincent, S., 2003. Left–right asymmetry: Notch acts upstream of Nodal. *Med. Sci. (Paris)* 19, 1188–1190.
- Vogan, K.J., Tabin, C.J., 1999. A new spin on handed asymmetry. *Nature* 295, 297–298.
- Wada, S., Katsuyama, Y., Yasugi, S., Saiga, H., 1995. Spatially and temporally regulated expression of the LIM class homeobox gene *Hrlim* suggests multiple distinct functions in development of the ascidian, *Halocynthia roretzi*. *Mech. Dev.* 51, 115–126.
- Waddington, C., 1937. The dependence of head curvature on the development of the heart in the chick embryo. *J. Exp. Biol.* 14, 229–231.
- Wall, N.A., Craig, E.J., Labosky, P.A., Kessler, D.S., 2000. Mesendoderm induction and reversal of left–right pattern by mouse *Gdf1*, a Vg1-related gene. *Dev. Biol.* 227, 495–509.
- Wang, D.Z., Reiter, R.S., Lin, J.L., Wang, Q., Williams, H.S., Krob, S.L., et al., 1999. Requirement of a novel gene, *Xin*, in cardiac morphogenesis. *Development* 126, 1281–1294.
- Wang, S., Yu, X., Zhang, T., Zhang, X., Zhang, Z., Chen, Y., 2004. Chick *Pcl2* regulates the left–right asymmetry by repressing *Shh* expression in Hensen's node. *Development* 131, 4381–4391.
- Ward, H.B., McLaren, A., Baker, T.G., 1987. Gonadal development in T16H/XSxr hermaphrodite mice. *J. Reprod. Fert.* 81, 295–300.
- Watanabe, D., Saijoh, Y., Nonaka, S., Sasaki, G., Ikawa, Y., Yokoyama, T., Hamada, H., 2003. The left–right determinant *Inversin* is a component of node monocilia and other 9+0 cilia. *Development* 130, 1725–1734.
- Wei, Y., Mikawa, T., 2000. Formation of the avian primitive streak from spatially restricted blastoderm: evidence for polarized cell division in the elongating streak. *Development* 127, 87–96.
- Weksberg, R., Shuman, C., Caluseriu, O., Smith, A.C., Fei, Y.L., Nishikawa, J., et al., 2002. Discordant *KCNQ1OT1* imprinting in sets of monozygotic twins discordant for Beckwith-Wiedemann syndrome. *Human Mol. Genet.* 11, 1317–1325.
- Welsh, I.C., O'Brien, T.P., 2000. Loss of late primitive streak mesoderm and interruption of left–right morphogenesis in the *Ednr $\beta$ (s-1Acrg)* mutant mouse. *Dev. Biol.* 225, 151–168.
- West, V.C., 1985. Case reports. Mirror image twins. *Aust. Orthodontic. J.* 9, 243.
- Winer-Muram, H., 1995. Adult presentation of heterotaxic syndromes and related complexes. *J. Thorac. Imag.* 10, 43–57.
- Wood, W.B., Kershaw, D., 1991. Handed asymmetry, handedness reversal and mechanisms of cell fate determination in nematode embryos. *Ciba Foundation Symposium* 162, 143–159; discussion 159–64.
- Wunsch, A., Little, C.D., Markwald, R.R., 1994. Cardiac endothelial heterogeneity is demonstrated by the diverse expression of JB3 antigen, a fibrillin-like protein of the endocardial cushion tissue. *Dev. Biol.* 165, 585–601.
- Xin, D., Bloomfield, S.A., 1997. Tracer coupling pattern of amacrine and ganglion cells in the rabbit retina. *J. Comp. Neurol.* 383, 512–528.
- Yager, J., 1984. Asymmetry in monozygotic twins. *Am. J. Psychiatry.* 141, 719–720.
- Yan, Y.T., Gritsman, K., Ding, J., Burdine, R.D., Corrales, J.D., Price, S.M., et al., 1999a. Conserved requirement for EGF-CFC genes in vertebrate left–right axis formation. *Genes Dev.* 13, 2527–2537.
- Yan, Y.T., Gritsman, K., Ding, J., Burdine, R.D., Corrales, J.D., Price, S.M., et al., 1999b. Conserved requirement for EGF-CFC genes in vertebrate left–right axis formation. *Genes Dev.* 13, 2527–2537.
- Yokouchi, Y., Vogan, K., Pearse, R., Tabin, C., 1999. Antagonistic signaling by *Caronte*, a novel Cerberus-related gene, establishes left–right asymmetric gene expression. *Cell* 98, 573–583.
- Yost, H.J., 1990a. Inhibition of proteoglycan synthesis eliminates left–right asymmetry in *Xenopus laevis* cardiac looping. *Development* 110, 865–874.
- Yost, H.J., 1990b. Inhibition of proteoglycan synthesis eliminates left–right asymmetry in *Xenopus laevis* cardiac looping. *Development* 110, 865–874.
- Yost, H.J., 1991. Development of the left–right axis in amphibians. *Ciba Foundation Symposium* 162, 165–176; discussion 176–81.
- Yost, H.J., 1992. Regulation of vertebrate left–right asymmetries by extracellular matrix. *Nature* 357, 158–161.
- Yost, H.J., 1998. Left–right development in *Xenopus* and zebrafish. *Sem. Cell Dev. Biol.* 9, 61–66.
- Yost, H.J., 2001. Establishment of left–right asymmetry. *Int. Rev. Cytol.* 203, 357–381.
- Yuan, S., Schoenwolf, G., 1998. De novo induction of the organizer and formation of the primitive streak in an experimental model of notochord reconstitution in avian embryos. *Development* 125, 201–213.
- Yuan, S., Schoenwolf, G.C., 2000. *Islet-1* marks the early heart rudiments and is asymmetrically expressed during early rotation of the foregut in the chick embryo. *Anatomical Rec.* 260, 204–207.
- Yue, X., Schultheiss, T.M., McKenzie, E.A., Rosenberg, R.D., 2004. Role of heparan sulfate in dextral heart looping in chick. *Glycobiology* 2004.
- Yuichiro I., Taku H., Atsuo N., Michael L., Amemiya, S., 2003. An inhibitor for H+/K+-ATPase disrupted the left–right asymmetry in the echinoid embryo. In: Annual Conference of Zoological Society of Japan.
- Zahs, K.R., 1998. Heterotypic coupling between glial cells of the mammalian central nervous system. *GLIA* 24, 85–96.
- Zahs, K., Newman, E., 1997. Asymmetric gap junctional coupling between glial cells in the rat retina. *GLIA* 20, 10–22.
- Zhang, X.M., Ramalho-Santos, M., McMahon, A.P., 2001. Smoothed mutants reveal redundant roles for *Shh* and *Ihh* signaling including regulation of L/R symmetry by the mouse node. [republished from *Cell*. 2001 Jun 15;105(6):781–92]. *Cell* 106, 781–792.
- Zhu, L., Marvin, M., Gardiner, A., Lassar, A., Mercola, M., Stern, C., Levin, M., 1999. *Cerberus* regulates left–right asymmetry of the embryonic head and heart. *Curr. Biol.* 9, 931–938.



## **Supplement 1:** molecular models of laterality defects in twins

As early as 1919, Spemann and Falkenberg (1919) reported that producing conjoined twins by tying a hair between the two blastomeres of amphibian eggs results in *situs inversus*, usually in the right twin. It has been proposed that an explanation for the rather surprising right-twin bias in laterality defects might be found in consideration of interactions between signaling molecules in two closely aligned primitive streaks. Analysis of spontaneous twins of chick embryos by *in situ* hybridization supports such models (Levin et al., 1996); these studies provide a partial understanding of laterality defects in human conjoined twins (Kapur et al., 1994).

These chick data give a context for considering the genesis of laterality defects in human beings. Several authors have modeled the origins of various classes of conjoined twins based on relative orientations of their primitive streaks at gastrulation (Kapur et al., 1994; Spencer, 1992; Spencer, 1995). In craniopagi and ischiopagi twins (joined at the head and abdomen respectively), which have not been described to exhibit laterality defects, the primitive streaks are end-to-end, and signaling molecules to the side of one would not be expected to affect the other. However, in dicephali (side-by-side twins possessing a single trunk), the two primitive streaks are modeled as being parallel to each other. By analogy to the chick, parallel streaks during early gastrulation could result in the right-sided Activin of the left embryo inhibiting the expression of Shh in the left side of the right embryo. This would result in a normal left embryo, but the right embryo would have no expression of Shh in the node, leading to lack of nodal expression. Since the lack of *nodal* expression results in random heart *situs* (Levin et

al., 1995). Randomized situs of the right embryo is precisely what Levin et al. found in their survey of dicephalus twins.

Thoracopagus (joined chest-to-chest) twins are thought to result from primitive streaks that are oriented more obliquely than those forming dicephalus twins. In such embryos, the two nodes become closer together as the streaks elongate. In some instances, the repression of *Shh* by *Activin* will proceed normally because the streaks will be too far apart for the signals to cross. However, as the embryos elongate anteriorly the *Shh* on the left side of the right embryo will cause nodal to be induced on the right side of the left embryo. In this case, the right embryo will be normal, but the left embryo will have double-sided nodal expression, leading to randomization of its *situs*. Thus, when primitive streaks are not completely parallel, which embryo has laterality defects will depend on their relative angle and distance apart. One would expect the left side twin to have laterality defects in a higher proportion of thoracopagus conjoined twins than in parapagus twins since they form at a more oblique angle. This is indeed what is observed.

Examining a number of spontaneous twin chick embryos (Levin et al., 1996), it was found that, as predicted, when twin primitive streaks are formed in a fully parallel orientation (as in dicephalus twins) *Shh* and *Nodal* were always expressed normally on the left of the left-side embryo, but never observed on either side of the right side embryo, suggesting cross-signaling by *Activin* between the two embryos at an early primitive-streak stage. In contrast, when twins form at an oblique angle (as in thoracopagus twins), nodal is expressed on both sides of the left-side embryo, and only

on the left of the right-side embryo, suggesting cross-signaling by Shh between the two embryos at the late primitive streak stage.

The *situs* defects occurring in conjoined twins from lateral transfer of asymmetric signals bring back into focus the problem of the midline barrier. While the notochord may serve a LR compartmentalization function in frogs or fish, and may be a barrier to the diffusion of the Nodal protein in chick, it is clearly not able to separate the early asymmetric signals in the normal chick node. Additional barrier mechanisms must exist at gastrulation. The expression of *Shh* on the left of the node which appears to be able to affect an adjacent twin across reasonably large distances in the blastoderm of conjoined embryos (see below), raises the question of why the protein does not affect the very near right side cells. The same problem occurs in the case of other soluble factors such as Activin, which are all expressed prior to the establishment of Lefty-mediated barriers. The molecular nature of the mechanisms which separate the L and R compartments at the beginning of gastrulation remains to be discovered, and may relate to a zone of midline cell death which has been described in the chick and shown to be an obligate aspect of correct LR asymmetry (Kelly et al., 2002).

**Supplement 2:** additional studies bearing on evolutionary conservation of LR mechanisms

An important difference in mechanisms upstream of Nodal may exist between chicks and *Xenopus*. While in chick embryos, the default state is lack of Nodal expression (*Shh* signaling is required to induce *Nodal* transcription on the left side

(Levin et al., 1995)), it was reported that explants of right lateral mesoderm from *Xenopus* embryos turn on XNR-1 expression (Lohr et al., 1997), arguing for an endogenous repressive influence from the midline. However, it was later demonstrated that explanted lateral tissue induces ectopic notochord-like structures containing *Shh* (in both frog and chick embryos), suggesting that an inductive pathway upstream of *Nodal* may actually be conserved in both species (Levin and Mercola, 1998).

Retinoic acid (RA), the active derivative of vitamin A which is known to regulate a number of patterning events, appears to interact with the LR pathway in a number of model systems. Excess RA as well as vitamin A deficiency are well known to disturb laterality of asymmetric organs, in particular the heart, but probably as a confluence of effects on both anteroposterior and LR patterning. Recent experiments in mice attempting to sort out the multiple effects of retinoid-dependent signaling show that RA treatment at the head-fold stage induced bilateral *nodal*, *lefty* and *Pitx2* genes while an RA antagonist can abolish expression in the LPM (for instance, (Chazaud et al., 1999; Tsukui et al., 1999), but without affecting *Shh* (Chen et al., 1996; Smith et al., 1997). It is not yet clear how to reconcile these results with the less severe effects on asymmetric gene expression seen in vitamin A deficient quails or mice lacking RALDH2, one of the enzymes involved in the formation of RA from vitamin A (Niederreither et al., 2001; Zile et al., 2000). The chick and quail data suggest that retinoids do not regulate the sidedness of gene expression, but might be required for maintaining adequate levels (Zile et al., 2000), and, importantly, are crucial for cardiac looping morphogenesis and patterning (Osmond et al., 1991). Consistent with this hypothesis, retinoids have recently been implicated in the morphogenesis, but not chirality, of the LR axis in

*Drosophila* embryos. In flies carrying “spin”, a novel, rotation-specific allele of the fasciclin2 cell-adhesion gene, abnormal endocrine function and an elevated level of juvenile hormone (an insect compound related to retinoic acid) lead to incomplete looping of the genitalia and spermiduct (Adam et al., 2003).

Gap junctions are known to play an important role in asymmetry in both chicks and frogs. What about mammals? No mouse mutants in gap junction genes have as yet reported a true LR phenotype; thus, knock-ins of dominant negative constructs will be required to determine whether GJC plays a role in LR asymmetry of rodents (since many different connexin genes exist in embryos and are thus potentially able to exhibit compensation during single gene deletion experiments). Significant insight into the evolutionary conservation of GJC mechanisms is expected from analysis of GJC in rabbits; the rabbit embryo exhibits circumferential patterns of connexin expression (Liptau and Viebahn, 1999), and functional analysis of GJC in a mammal with the flat architecture of the chick is likely to shed significant light on the evolutionary conservation and origin of the GJC system as it participates in LR patterning.

### **Supplement 3:** ultimate origins

The issue of original chirality (i.e., why living organisms contain only L-amino acids and D-sugars) is also a very interesting one, and is bound up fundamentally with the origin of life. Pasteur (Pasteur, 1860) showed that *in vitro* synthesis invariably results in equal mixtures of enantiomer pairs of compounds, while biosynthetic processes were able to clearly separate such racemic mixtures. Several theories for this



have been proposed. Perhaps, whatever type of isomer happened to have formed first biased the rest of evolution towards that type by competition (Frank, 1953). The chirality of the first one could have been determined by chance, or by exogenous factors such as the Coriolis force, light (Noyes and Bonner, 1975) or even the geomagnetic field. Interestingly, the GMF seems to have a relationship with LR chirality (Anderson, 1988). The geological fossil record shows a correlation between flipping of the GMF polarity and reversals of the chirality of several types of molluscs such as *Globorotalia menardi* (Dubrov, 1978; Harrison and Funnel, 1964). Thus, the determination of chirality may be one of the several roles the GMF probably plays in embryogenesis (Asashima et al., 1991; Cole and Graf, 1974; Leal et al., 1992; Sandoze et al., 1995; Shibib et al., 1987).

Alternatively, there may be a fundamental reason for why biological forms prefer one type of molecule over its enantiomer. For example, Garay (Garay, 1968) has shown that when racemic mixtures of the amino acids alanine, tryptophan, and tyrosine in alkaline solution are subjected to decomposition by radio-active decay of strontium-90, the D-isomers are destroyed more quickly than the L-isomer. There are also arguments (Kondepudi, 1987; Mason and Tranter, 1984) based on weak neutral currents which show that L-amino acids will predominate in a period of on the order of 15,000 years. Thus, radioactive decay could plausibly have biased enantiomer choice in the pre-biotic environment. Likewise, the energy of the right-handed  $\alpha$ -helix of poly-L-alanine is a few tenths of a kilocalorie per mole per residue lower than that of the left-handed helix, implying that over some length, the right-handed forms will be more stable (Morgan, 1977). Both asymmetries are presumably consequences of the non-conservation of parity in sub-atomic weak nuclear interactions (Wu et al., 1957).

## References

- Adam, G., Perrimon, N. and Noselli, S. (2003) The retinoic-like juvenile hormone controls the looping of left-right asymmetric organs in *Drosophila*. *Development* 130, 2397-406.
- Anderson, B. (1988) On morphogenesis. *Medical Hypotheses* 26, 183-186.
- Asashima, M., Shimada, K. and Pfeiffer, C. (1991) Magnetic shielding induces early developmental abnormalities in the newt. *Bioelectromagnetics* 12, 215-224.
- Chazaud, C., Chambon, P. and Dolle, P. (1999) Retinoic acid is required in the mouse embryo for left-right asymmetry determination and heart morphogenesis. *Development* 126, 2589-96.
- Chen, Y., Dong, D., Kostetskii, I. and Zile, M.H. (1996) Hensen's node from vitamin A-deficient quail embryo induces chick limb bud duplication and retains its normal asymmetric expression of Sonic hedgehog (Shh). *Developmental Biology* 173, 256-264.
- Cole, F. and Graf, E. (1974) Precambrian ELF and abiogenesis. In Persinger, M. (ed.), *ELF and VLS Electromagnetic Field Effects*, Plenum Press, New York.
- Dubrov, A. (1978) *The Geomagnetic Field and Life*. Plenum Press, New York.
- Frank, F.C. (1953) On spontaneous asymmetric synthesis. *Biochem. Biophys. Acta.* 11, 459-463.
- Garay, A. (1968) Origin and role of optical isomery in life. *Nature* 219, 338-340.
- Harrison, C. and Funnel, B. (1964) Relationship of paleomagnetic reversals and micropaleontology in two late Caenozoic cores from the Pacific Ocean. *Nature* 204, 566-.
- Kapur, R., Jack, R. and Siebert, J. (1994) Diamniotic placentation associated with omphalopagus conjoined twins. *American Journal of Medical Genetics* 52, 188-95.
- Kelly, K., Wei, Y. and Mikawa, T. (2002) Cell death along the embryo midline regulates left-right sidedness. *Developmental Dynamics* 224, 238-44.
- Kondepudi, D.K. (1987) Selection of molecular chirality by extremely weak chiral interactions under far-from-equilibrium conditions. *Biosystems* 20, 75-83.
- Leal, J., Abaira, V., Trillo, M., Ubeda, A. and Chacon, L. (1992) Embryonic development and earth's MF. *First World Congress on Electric and Magnetic Fields in Biology*.
- Levin, M., Johnson, R., Stern, C., Kuehn, M. and Tabin, C. (1995) A molecular pathway determining left-right asymmetry in chick embryogenesis. *Cell* 82, 803-814.
- Levin, M. and Mercola, M. (1998) Evolutionary conservation of mechanisms upstream of asymmetrical nodal expression: reconciling the chick and frog. *Developmental Genetics* 23, 185-193.
- Levin, M., Roberts, D., Holmes, L. and Tabin, C. (1996) Laterality defects in conjoined twins. *Nature* 384, 321.
- Liptau, H. and Viebahn, C. (1999) Expression patterns of gap junctional proteins connexin 32 and 43 suggest new communication compartments in the gastrulating rabbit embryo. *Differentiation* 65, 209-19.

- Lohr, J.L., Danos, M.C. and Yost, H.J. (1997) Left-right asymmetry of a nodal-related gene is regulated by dorsoanterior midline structures during *Xenopus* development. *Development - Supplement* 124, 1465-72.
- Mason, S. and Tranter, G. (1984) The parity-violating energy differences between enantiomeric molecules. *Molecular Physics* 53, 1091-1111.
- Morgan, M. (1977) Embryology and Inheritance of Asymmetry. In Harnad, S. (ed.), *Lateralization in the Nervous System*, Academic Press, New York, pp. 173-194.
- Niederreither, K., Vermot, J., Messaddeq, N., Schuhbauer, B., Chambon, P. and Dolle, P. (2001) Embryonic retinoic acid synthesis is essential for heart morphogenesis in the mouse. *Development* 128, 1019-31.
- Noyes, H.P. and Bonner, W.A. (1975) On the origin of molecular "handedness" in living systems. *Journal of Molecular Evolution* 6, 91-98.
- Osmond, M.K., Butler, A.J., Voon, F.C.T. and Bellairs, R. (1991) The effects of retinoic acid on heart formation in the early chick embryo. *Development* 113, 1405-1417.
- Pasteur, L. (1860) *Researches on molecular asymmetry*. In, *Alembic Club Reprint* 14Edinburgh.
- Sandoze, V., Svanidze, I. and Didimova, E. (1995) Effects of the action of a hypomagnetic field in the motor activity of ciliary apparatus of ependymal cells *in vivo*. *Radiotzionnaya Biologia Radioekologia* 35, 19-22.
- Shibib, K., Brock, M. and Gosztony, G. (1987) The geomagnetic field: a factor in cellular interactions. *Neurology Research* 9, 225-235.
- Smith, S.M., Dickman, E.D., Thompson, R.P., Sinning, A.R., Wunsch, A.M. and Markwald, R.R. (1997) Retinoic acid directs cardiac laterality and the expression of early markers of precardiac asymmetry. *Dev Biol* 182, 162-71.
- Spemann, H. and Falkenberg, H. (1919) Über Asymmetrische Entwicklung und Situs inversus viscerum bei Zwillingen und Doppelbildungen. *Wilhelm Roux' Archives Entwicklungsmechanik Organismen* 45, 371-422.
- Spencer, R. (1992) Conjoined twins: theoretical embryologic basis. *Teratology* 45, 591-602.
- Spencer, R. (1995) Rachipagus conjoined twins: they really do occur. *Teratology* 52, 346-56.
- Tsukui, T., Capdevila, J., Tamura, K., Ruiz-Lozano, P., Rodriguez-Esteban, C., Yonei-Tamura, S., Magallon, J., Chandraratna, R.A., Chien, K., Blumberg, B., Evans, R.M. and Belmonte, J.C. (1999) Multiple left-right asymmetry defects in *Shh(-/-)* mutant mice unveil a convergence of the *shh* and retinoic acid pathways in the control of *Lefty-1*. *Proceedings of the National Academy of Sciences of the United States of America* 96, 11376-81.
- Wu, C., Ambler, E., Hayward, R., Hoppes, D. and Hudson, R. (1957) Experimental test of parity conservation in beta decay. *Physical review* 105, 1413.
- Zile, M.H., Kostetskii, I., Yuan, S., Kostetskaia, E., St Amand, T.R., Chen, Y. and Jiang, W. (2000) Retinoid signaling is required to complete the vertebrate cardiac left/right asymmetry pathway. *Developmental Biology* 223, 323-38.

Corrigendum

Corrigendum to “Left–right asymmetry in embryonic development:  
a comprehensive review” [Mech. Dev. 122 (2005) 3–25]<sup>☆</sup>

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The author regrets that in the above article, Table 2 contained two erroneous references.

For the “Leftover” row, the citation should be Gamse et al. (2003). For the “Cyclops” row, the references should be:

Sampath, K., Rubinstein, A.L., Cheng, A.M., Liang, J.O., Fekany, K., Solnica-Krezel, L., Korzh, V., Halpern, M.E., Wright, C.V., 1998. Induction of the zebrafish ventral brain and floorplate requires cyclops/nodal signalling. *Nature* 395 (6698), 185–189.

Rebagliati, M.R., Toyama, R., Haffter, P., Dawid, I.B., 1998. Cyclops encodes a nodal-related factor involved in midline signaling. *Proc. Natl Acad. Sci. USA* 95 (17), 9932–9937.

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