Cell fate decisions and axis determination in the early mouse embryo

Katsuyoshi Takaoka¹,² and Hiroshi Hamada¹,²

Summary
The mouse embryo generates multiple cell lineages, as well as its future body axes in the early phase of its development. The early cell fate decisions lead to the generation of three lineages in the pre-implantation embryo: the epiblast, the primitive endoderm and the trophectoderm. Shortly after implantation, the anterior-posterior axis is firmly established. Recent studies have provided a better understanding of how the earliest cell fate decisions are regulated in the pre-implantation embryo, and how and when the body axes are established in the pregastrulation embryo. In this review, we address the timing of the first cell fate decisions and of the establishment of embryonic polarity, and we ask how far back one can trace their origins.

Key words: AP axis, Blastocyst, Cell fate, Trophoderm, Inner cell mass, Primitive endoderm

Introduction
The early development of the mouse embryo, from a fertilized egg to a gastrulating embryo, involves a tightly regulated series of lineage specification events and the simultaneous establishment of the embryonic axes (Fig. 1). These events include the formation of a blastocyst, following compaction (see Glossary, Box 1) at embryonic day (E) 3.5, when cells then go on to form either the trophectoderm (TE, see Glossary, Box 1) or inner cell mass (ICM), from which the epiblast (Epi, see Glossary, Box 1) or primitive endoderm (PrE, see Glossary, Box 1) are subsequently derived.

Given that the mouse embryo begins life as one cell, the fertilized egg must perform at least three tasks during the early phase of development. It must: (1) increase the number of cells by proliferation; (2) increase the number of cell types by differentiation; and (3) generate polarity to allow the establishment of the future body axis. How can an embryo generate multiple types of cells and polarities when it starts out as a single cell? Where do the initial signals for the induction of cell differentiation and for the generation of asymmetries come from?

Diverse mechanisms to establish early polarity are known to operate in various organisms (Kloc and Etkin, 2005; Schneider and Bowerman, 2003; St Johnston, 2005), but let us think of two extreme scenarios (Fig. 2). In one scenario, there is a determinant in a specific region of the oocyte, and this determinant becomes asymmetrically distributed after fertilization. This determinant can thus be inherited asymmetrically as the fertilized egg divides. A blastomere that receives this determinant will adopt a cell fate that is different from a blastomere that does not receive the determinant, resulting in the generation of two cell types or of a polarity within the embryo. Bicoid in Drosophila (Huynh and St Johnston, 2004) and Macho-1 in ascidians (Nishida and Sawada, 2001) are examples of such determinants. In the second scenario, the embryo does not have such a localized maternal determinant, so it must make use of some other signal(s) to generate polarity and different cell types.

The current view is that the mouse embryo probably conforms to the second scenario. Fertilized mouse embryos inherit maternal RNA and proteins. Some of these maternal factors persist until the blastocyst stage, while zygotic gene expression begins at the two-cell stage (Carter et al., 2003; Wang et al., 2004). Although early development of the mouse embryo absolutely requires maternal transcripts and proteins (Li et al., 2010), there is no evidence that maternal determinants are localized. As such, the mouse embryo develops from fertilization to gastrulation through a series of cell type specifications and body axis determinants, which most probably occur in the absence of an asymmetrically localized maternal determinant.

Here, we review the mechanisms used to determine cell fate and the timing of these cell fate decisions in the early mouse embryo. We also review these cell fate decisions in relation to the establishment of the embryonic axes. As it is premature to conclude that maternal determinants are absent in mammals, we also discuss how far back we can trace the onset of cell specification and embryonic polarity in the mouse embryo.

The first cell fate decision: inner cell mass or trophectoderm
Generation and translation of inside-outside polarity
The fertilized mouse egg reaches the eight-cell stage after three rounds of cell division. The embryo then undergoes an event known as compaction in which an increase in cell-cell contact promotes cell adhesion (Fig. 1). Compaction generates apical-basal polarity in each cell of the eight-cell embryo. Proteins related to the establishment of cellular polarity, such as Ezrin, protein kinase C (PKC), Par3 (partitioning defective; Pard3 – Mouse Genome Informatics), Par6 (partitioning defective 6; Pard6α – Mouse Genome Informatics) and atypical PKC (aPKC) localize asymmetrically to the apical side of the compacted morula (Pauken and Capco, 2000; Plusa et al., 2005; Vinot et al., 2005). By contrast, proteins such as Par1 (partitioning defective 1b; Mark2 – Mouse Genome Informatics) and E-cadherin (Hyafil et al., 1980; Shirayoshi et al., 1983; Vinot et al., 2005) localize to the basolateral side of the cells. Thus, by the early morula stage, at E2.5, each cell of the compacted embryo possesses distinct apical-basal polarity.

Following this, the cells of the morula undergo further cleavages to generate the blastocyst. Given that the orientation of the mitotic spindle is random during the fourth division, both symmetric and asymmetric divisions can occur, depending on the orientation of the spindle with respect to the apical-basal polarity (Johnson and Ziomek, 1981). Two rounds or ‘waves’ of asymmetric cell division
underlie the development of the embryo from the eight-cell to the 16-cell stage and from the 16-cell to the 32-cell stage, and these result in the generation of outside cells and inside cells (Tarkowski and Wroblewska, 1967). This inside-outside polarity leads to differential Hippo signaling that is dependent on cell position within the embryo (Nishioka et al., 2009). Hippo signaling is a signaling pathway that involves a serine/threonine (Ser/Thr) kinase called Hippo in *Drosophila* and Stk3 (Ser/Thr kinase 3)/Mst in the mouse. It controls cell contact-mediated inhibition of proliferation (Pan, 2007; Saucedo and Edgar, 2007) and is activated only in the inside cells that are surrounded entirely by other cells, not in outer cells (Fig. 3A). In inner cells, Hippo activation results in the phosphorylation of the transcriptional co-activator Yes-associated protein (Yap1) and thereby prevents its translocation to the nucleus. In the absence of nuclear Yap1, its partner, the TEA domain family transcription factor 4 (Tead4), is unable to activate target genes. In the outside cells, however, Hippo signaling is downregulated because their apical side is not in contact with other cells, and an unknown apical signal may also repress the Hippo pathway. Yap1 thus remains unphosphorylated in these cells, and it therefore enters the nucleus, binds to Tead4 and activates TE-specific genes such as caudal-related homeobox 2 (*Cdx2*). Mutant embryos lacking Tead4 no longer manifest *Cdx2* expression and are unable to generate TE (Nishioka et al., 2008; Yagi et al., 2007).

**ICM and TE establishment by a transcription factor network**

By E3.5, two types of cells can be found in the blastocyst: TE cells and ICM cells. *Cdx2* is a functional marker for TE, whereas the pluripotency-associated transcription factors Oct3/4 (POU domain, class 5, transcription factor 1, Pou5f1 – Mouse Genome Informatics) and Nanog are functional markers for the ICM. These transcription factors show dynamic expression patterns between the morula and blastocyst stages (Dietrich and Hiiragi, 2007; Niwa et al., 2005). Of these genes, *Cdx2* is the first to show a restricted pattern of gene expression. It is preferentially expressed in the outside cells at the early blastocyst stage (at around E3.0, between the 16- and 32-cell stages), whereas *Oct3/4* is expressed uniformly at this stage (Niwa et al., 2005). The level of *Nanog* expression varies among blastomeres, but this variation is independent of blastomere position within the embryo (Dietrich and Hiiragi, 2007). There is therefore initially no apparent reciprocal relationship between *Cdx2* and *Oct3/4* expression or between *Cdx2* and *Nanog* expression. As development proceeds, however, *Cdx2* expression becomes restricted to the outside future TE cells, whereas the expression of *Oct3/4* and *Nanog* gradually becomes confined to the inside future ICM cells. This reciprocal expression pattern of *Cdx2* and *Oct3/4* is achieved by the operation of double negative-feedback loops that are mediated by the transcription factors they
encode (Niwa et al., 2005) (Fig. 3B). In fact, a zygotic Cdx2 mutant is able to form embryos containing cells that resemble TE cells morphologically but that ectopically express Oct3/4 and Nanog and are negative for TE markers (Strumpf et al., 2005). Conversely, downregulation of Oct3/4 expression or the forced expression of Cdx2 in embryonic stem (ES) cells results in their differentiation into the TE lineage (Niwa et al., 2005). In addition, the transcription factor Gata3 (GATA-binding protein 3) promotes differentiation into the TE lineage downstream of Tead4 and in parallel to Cdx2 (Fig. 3B) (Ralston et al., 2010).

Onset of ICM versus TE fate

As mentioned above, the first cell fate decision has been thought to be based on the differential positioning of cells on the inside or outside of the embryo around the 16-cell stage (Johnson and McConnell, 2004; Tarkowski and Wroblewska, 1967). If this is the case, the initial signal that induces the first cell differentiation event would arise from the inside-outside (apical-basal) information that is generated by compaction, which begins at the eight-cell stage. However, recent studies have detected molecular differences among blastomeres as early as the four-cell stage, which indicates that the onset of the first cell fate decision may occur earlier. The earliest molecular differences between blastomeres that have been described to date relate to histone modifications. At E3.5, the cells of the ICM and TE exhibit differences in various types of histone modifications (Erhardt et al., 2003; Reik et al., 2003). For example, the levels of H4K8ac (acetylation of histone H4 at lysine 8) and H3K4me3 (trimethylation of histone H3 at lysine 4), both example, the levels of H4K8ac (acetylation of histone H4 at lysine 8) and H3K4me3 (trimethylation of histone H3 at lysine 4), both of which are epigenetic marks associated with active chromatin, in the promoter region of Oct3/4 are higher in cells of the ICM than in those of the TE (VerMilyea et al., 2009). However, the extent of H3K9me2 (dimethylation of histone H3 at lysine 9), which is a repressive epigenetic mark, in the promoter regions of Oct3/4 and Nanog is lower in ICM cells than in TE cells. The promoter region of Cdx2 shows a reverse pattern, with the levels of H4K8ac and H3K4me3 being higher in TE than in ICM cells (VerMilyea et al., 2009). Unexpectedly, the global levels of H3R17me and H3R26me (monomethylation of histone H3 at arginines 17 and 26, respectively) were found to differ among blastomeres of four-cell stage embryos that have undergone tetrahedral division patterns (Torres-Padilla et al., 2007a). Those cells showing higher levels of H3R17me and H3R26me are biased to become ICM, whereas those with lower levels are preferentially fated to become TE. Furthermore, injection of an expression vector for Carm1 (an H3-specific arginine methyltransferase that is responsible for the generation of H3R17me and H3R26me) into one blastomere of a two-cell embryo resulted in the upregulation of Nanog and Sox2 expression in the injected cell and its preferential contribution to the ICM (Parfitt and Zernicka-Goetz, 2010). Although Carm1 mutant mice develop normally until late embryonic stages, it is possible that Carm1 may function as a maternal factor. There may be epigenetic differences between early blastomeres, but a recent transcriptome analysis has failed to detect asymmetry between blastomeres at two-cell and three-cell stages (VerMilyea et al., 2011).

Fig. 2. Two possible mechanisms for the generation of multiple cell types and polarity. (A) Localized maternal determinant. In this model, a maternal determinant (pink) is unevenly distributed in the oocyte, and hence in the fertilized egg, and becomes inherited asymmetrically by daughter cells following cell division. The blastomere that receives this determinant can therefore adopt a cell fate that is different from a blastomere that does not receive the determinant. This can allow the generation of two cell types, as well as polarity, within the developing embryo. (B) No localized maternal determinant. In the absence of such an asymmetrically localized maternal determinant, alternatives mechanisms must exist to allow the generation of multiples cell types and polarity within the embryo.
It will be interesting to examine the relationship between these two molecular differences: that in H3R17me and H3R26me at the four-cell stage; and that in Oct3/4 behavior at the four- and eight-cell stages (Fig. 4). If a direct link exists, a group of cells with higher levels of H3R17me and H3R26me would correspond to those with immobile Oct3/4. Higher levels of H3R17me and H3R26me in the genome might increase the accessibility of Oct3/4 to its targets sites, which would result in activation of its target genes. In which case, how and when is this differential histone modification generated? Why does a blastomere with low Oct3/4 kinetics preferentially undergo asymmetric division? Many questions about these findings remain to be addressed.

**The second fate decision: epiblast or primitive endoderm**

By E4.5, overt segregation of primitive endoderm (PrE) and the epiblast has occurred in the ICM, with the two types of cells showing clear segregation in terms of their positions and molecular markers (Fig. 1). On the one hand, the PrE comprises a layer of cells on the surface of the ICM, forming the cells that face the blastocoel cavity, and are positive for specific markers, such as Gata6 and Gata4 (members of the GATA family of transcription factors). On the other hand, the epiblast, which is positive for Nanog and Oct3/4, is located inside the ICM. However, the cell fate decision of PrE versus epiblast occurs earlier than E4.5. At E3.5, two types of cells, one type positive for Nanog and the other positive for Gata6, are present within the ICM in a ‘salt-and-pepper’ pattern, suggesting that most ICM cells have already determined their fate as either PrE or epiblast (Chazaud et al., 2006) (Fig. 5A). Live imaging has confirmed that most of the cells positive for platelet-derived growth factor receptor α (PDGFRα), a marker for PrE, are randomly positioned in the ICM at E3.5 and will move to the surface of the ICM that faces the blastocoel cavity and eventually become PrE (Plusa et al., 2008). A minority of blastomeres in the ICM at E3.5 may remain naïve, however. Thus, some of the PDGFRα-positive cells do not express Gata6 and Gata4 (Plusa et al., 2008). Likewise, cells that are positive for the Nodal antagonist Lefty1 (left-right determination factor) at E3.5 will contribute to the epiblast, but about 20% of such cells are positive for Gata6 (instead of Nanog) at this stage (Takaoka et al., 2011). The analysis of gene expression in single cells (Guo et al., 2010) has revealed that progressive changes in molecular signature occur during blastocyst formation. Nanog and Gata6 are thus co-expressed at the morula stage (eight cells) and at the late blastocyst stage (16 cells), they then undergo gradual upregulation or downregulation around the 32-cell stage, and are finally expressed in a mutually exclusive manner at the late blastocyst stage (64 cells).

The segregation of the epiblast and PrE lineages in the ICM is known to be regulated by fibroblast growth factor (FGF) signaling (Lanner and Rossant, 2010) (Fig. 5B). Fgf4, FGF receptor 2 (Fgfr2) and an SH2/SH3 adaptor (Grb2), which together mediate activation of the mitogen-activated protein kinase (Mapk) signaling pathway, are all necessary for PrE formation. In mouse embryos lacking Grb2, for example, all ICM cells are positive for Nanog and negative for Gata6, suggesting that they have adopted the epiblast fate at the expense of PrE (Arman et al., 1998; Cheng et al., 1998; Feldman et al., 1995; Mitsui et al., 2003; Wilder et al., 1997). Furthermore, experimental manipulation of FGF signaling can change the fate of ICM cells. Inhibitors of such signaling have thus been shown to shift ICM cells to the epiblast fate, whereas excess FGF shifts them to PrE (Yamanaka et al., 2010). In support of this, treatment of the eight-cell stage embryo with FGF signaling inhibitors eliminates PrE and expands the epiblast (Nichols et al., 2009).

Is the decision to form PrE versus epiblast dependent on cell lineage history? Does PrE originate preferentially from any of the cells generated by asymmetric cell division between the eight- and 32-cell stages, for example? Live cell tracing from the eight-cell stage onwards (Morris et al., 2010) revealed that cells internalized by the first wave of asymmetric cell division are biased toward the epiblast, whereas inner cells generated by the second wave of
of exogenous FGF to the culture medium inhibits Nanog expression in these cells (Hamazaki et al., 2006); however, the addition of FGF signaling inhibitors stabilizes Nanog expression (Lanner et al., 2010).

The sorting mechanism responsible for the relocation of randomly positioned PrE progenitor cells to the surface of the ICM facing the blastocoel remains unknown (Fig. 5). In this regard, Dab2 (disabled homolog 2) mutant embryos show an interesting phenotype: PrE progenitor cells form in this mutant but are unable to move to the surface of the ICM (Yang et al., 2002). Dab2 is thought to function as a cargo-selective endocytic adaptor that links clathrin-coated endocytic vesicles to actin-based myosin V1 (Morris et al., 2002). In the E4.5 embryo, Dab2, together with Lrp2 (low density lipoprotein receptor-related protein 2), is localized to the apical surface of PrE cells. The distribution of Dab2 and Lrp2 may become polarized according to embryonic-abembryonic positional information, and the polarized localization of Dab2 may facilitate directional trafficking of an unknown protein, such as a cell-adhesion protein. Such a scenario would achieve cell-autonomous cell sorting, but it may be informative to characterize the dynamics of the localization of Dab2 and Lrp2 during the movement of PrE progenitor cells to the apical surface of the ICM; Lrp2 is expressed in PrE progenitor cells at E3.5, although Dab2 is not detected at this time (Gerbe et al., 2008). In addition, there may be positional signals from the blastocoel cavity that attract migration towards the cavity. For example, Wnt9a, which is expressed in cells that surround the blastocoel cavity that attract migration towards the cavity. For example, Wnt9a, which is expressed in cells that surround the blastocoel cavity, facilitates the repositioning of Gata4-expressing cells (Meilhac et al., 2009). Finally, cells that are incorrectly positioned during cell sorting may undergo apoptosis.

The origin of body axes: asymmetries in the blastocyst

The embryonic-abembryonic axis

Pre-implantation mouse embryos exhibit a few morphological asymmetries. For example, the sperm entry site, which is known to provide a cue for embryonic patterning in other animals, such as Xenopus (Gerhart et al., 1989), is located on one side of the fertilized egg. In addition, at the two-cell stage, the second polar body is located on one side between the two blastomeres. It continues to be located on one side of the embryo until the blastocyst stage (Gardner, 1997). The zona pellucida also persists as an oval rather than as a sphere. Finally, the formation of the ICM and the blastocoel cavity in the blastocyst generates the embryonic-abembryonic axis, which is perpendicular to the border between the embryonic and the blastocoel (see Box 2). Given that the embryonic-abembryonic axis corresponds to the long axis (the proximal-distal axis) of the embryo at the egg cylinder stage (E5.5; see Glossary, Box 1), which in turn will correspond to the dorsal-ventral axis, it can be regarded as the source of future dorsal-ventral polarity (Rossant and Tam, 2009).

Whether a direct link exists between the embryonic-abembryonic axis and the earlier morphological asymmetries is a controversial issue (see Box 2). Whereas some findings have indicated the existence of a direct relationship between the sperm entry site, the position of the second polar body at the two-cell stage and the embryonic-abembryonic axis in the blastocyst (Gardner, 1997; Piotrowska and Zernicka-Goetz, 2001; Plusa et al., 2005), others argue against such a direct interaction (Hiiragi and Solter, 2004; Kurotaki et al., 2007). Differences in the techniques used may underlie these discrepancies, but it is difficult to reconcile these two sets of findings at this time.
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Although the formation of the AVE marks the firm establishment of the AP axis, it has become increasingly apparent that AP polarity originates much earlier – at the blastocyst stage at the latest. In particular, a recent study (Takaoka et al., 2011) has shown that the origins of the AVE and DVE are different, and that cells of the DVE originate in the blastocyst. Based on these findings, it is necessary to define clearly the DVE and the AVE (Fig. 6). The DVE comprises a group of cells that express Lefty1 and Cer1 at the distal end of the E5.5 embryo, whereas the AVE consists of a group of cells that begin to express the same genes at the distal end after E5.5. Coincidentally, both DVE and AVE cells express the same set of marker genes, including Lefty1, Cer1 and Hhex (Hex, hematopoietically expressed homeobox), although there is some heterogeneity among the two cell populations. Furthermore, both the DVE and the AVE migrate in the same direction, towards the future anterior side. Given these observations, the prevailing view was that AVE cells descend directly from DVE. However, recent genetic fate mapping and live imaging have revealed that they have different origins (Takaoka et al., 2011). In this study, the DVE was shown to be derived from Gata6Lefty1c cells that first appear around E4.0, although the generation of fully differentiated DVE cells requires additional gene expression around E5.5. By contrast, the AVE is derived from Gata6Lefty1cVE cells that move to the distal tip of the embryo and begin to express Lefty1 and Cer1 after E5.5 (see below).

Lefty1 expression begins in a subset of blastomeres in the ICM at E3.5 (Takaoka et al., 2006; Takaoka et al., 2011). Most of these Lefty1c cells are Gata6+ (some are Gata6c), but this heterogeneity most probably reflects the fact that some ICM cells at this stage are...
still naïve, as described above). However, these cells rapidly lose Lefty1 expression and eventually contribute to the epiblast. The biological relevance of the epiblast-fated Lefty1+ cells is unknown, but they may be required to induce the subsequent Lefty1 expression in Gata6+ cells at E4.0 or to pattern the epiblast before gastrulation. A second wave of Lefty1 expression takes place in Gata6+ cells around E3.75 to E4.0. These Lefty1+ cells become asymmetrically located at the upper side of the PrE in the tilted embryo at E4.2 (Takaoka et al., 2006) (Fig. 6) and will contribute to the epiblast by constituting a reaction/diffusion-type regulatory system. If Lefty1 expression is maintained throughout the cell lineage that gives rise to the DVE, asymmetrically located Lefty1+ cells can be generated by culturing blastocysts in vitro (Takaoka et al., 2006). Furthermore, these in vitro-generated Lefty1+ cells contribute to the DVE when the cultured blastocyst is returned to a pseudo-pregnant female (Takaoka et al., 2011). These observations suggest that initial AP polarity is specified autonomously without information from the uterus.

Given that the Gata6+Lefty1+ cells in the blastocyst contribute to the DVE, the origin of AP polarity can be traced back at least to these Lefty1+ cells in the blastocyst. It has been reported that Cer1 expression also initiates in a subset of PrE cells of the E4.25 expanded blastocyst, possibly in the same cells that are positive for Lefty1 expression (Torres-Padilla et al., 2007b). The next important issue concerns how future DVE cells are selected among PrE progenitor cells in the blastocyst: that is, how Lefty1 expression is restricted to a subset of PrE progenitor cells. Lefty1 expression in the PrE at E4.5 and in the DVE at E5.5 depends on the Nodal-responsive Foxh1 (forkhead box H1)-dependent enhancer located in the 5’ upstream region of Lefty1 (Takaoka et al., 2006). If Lefty1 expression in the earlier blastocyst also depends on this enhancer, Nodal signaling may contribute to the regulation of Lefty1, given that it regulates Lefty1 and Lefty2 expression during left-right patterning at a later stage by constituting a reaction/diffusion-type regulatory system (Nakamura et al., 2006). In this regard, it is interesting to note that the Foxh1-dependent enhancer of Nodal is active in a subset of ICM cells in the blastocyst (Granier et al., 2011) and that Furin and Pace4 (Pcsk6 – Mouse Genome Informatics), secreted protein convertases that can process Nodal precursor to its active form, are already active at the blastocyst stage in the ICM (Mesnard et al., 2006). Additional asymmetries have also been described in the peri-implantation embryo. For example, nuclear localization of β-catenin is detected in a subset of epiblast cells at E4.5 (Chazaud et
al., 2006). Furthermore, the Wnt/β-catenin-dependent enhancer (PEE) of Nodal can mark a subset of blastomeres in the blastocyst (Granier et al., 2011). There may thus be an asymmetry at the level of canonical Wnt signaling within the blastocyst and the implanting embryo, although its relevance remains to be determined. It will be interesting to learn how each asymmetry relates to the other.

Establishment of the AP axis
Behavior of the DVE and newly generated AVE
Although Lefty1 expression is maintained in the DVE-fated cells, Lefty1+ prospective DVE cells before E5.5 do not express other DVE markers such as Cer1 and Hhex (Mesnard et al., 2006), although Cer1 has been detected prior to this (Torres-Padilla et al., 2007b). Expression of Cer1 and Hhex begins in DVE cells at E5.5 (Mesnard et al., 2006). The complete differentiation of DVE cells may therefore require the expression of additional DVE-specific genes. Interestingly, DVE cells change their shape between E5.0 and E5.5: Lefty1+ prospective DVE cells at E5.0 are cuboidal, whereas DVE cells at E5.5 are columnar. Fully specified DVE cells at E5.5 begin to migrate unilaterally towards the proximal side. When they reach the embryonic/extra-embryonic junction, they migrate back in the lateral-distal direction and rapidly lose expression of Lefty1 (and of other DVE markers) (Takaoka et al., 2011).

Despite the fact that the AVE expresses the same set of genes and migrates in the same direction as does the DVE, the origin of the AVE differs from that of the DVE (Takaoka et al., 2011). AVE is thus newly formed from Gata6+Lefty1– VE cells. These AVE progenitor cells are initially located in a more proximal region at E5.5, move towards the distal side and begin to express AVE markers when they reach the distal end (Fig. 6). This scenario was previously suggested by fate-mapping analysis with HRP and by time-lapse observation of cells labeled with a Hhex-GFP transgene (Perea-Gomez et al., 2001; Rivera-Perez et al., 2003), but it was only clearly demonstrated by recent genetic fate-mapping and live imaging studies (Takaoka et al., 2011). AVE formation is inhibited by signals that originate from the extra-embryonic ectoderm, most probably bone morphogenetic protein (BMP) (Yamamoto et al., 2009). Thus, AVE progenitors may begin to express AVE markers when they reach the distal end because it is the only region that is negative for the BMP signal in the embryo proper (Yamamoto et al., 2009). Newly formed AVE cells also migrate towards the proximal side, following DVE, and they occupy the future anterior side of the embryo at E6.5.

DVE and AVE migration: driving forces and cellular mechanisms
How is the migration of the DVE and the AVE regulated? What might be the driving forces of such migration and are there instructive signals that attract the cells?

DVE cells change their shape and become columnar by the time they start to migrate (Migeotte et al., 2010; Rivera-Perez et al., 2003; Takaoka et al., 2011). Given that the VE is a monolayer of cells, DVE cells must migrate through the surrounding VE cells rather than on top of them (Srinivas et al., 2004). Migrating DVE cells acquire a snail-like morphology with a highly elongated lamella terminating in two lateral horn-like protrusions; these filopodium-like protrusions are polarized in the direction of cell movement (Migeotte et al., 2010). DVE cells retain cell-cell junctions during migration and display the hallmarks of a collective cell movement (Migeotte et al., 2010; Srinivas et al., 2004). In a mutant mouse that lacks the Rho GTPase family member Rac1 (RAS-related C3 botulinum substrate 1), DVE cells are unable to change their shape and to form the filopodium-like structures, and they fail to migrate away from the distal side of the embryo. Rac1 appears to act autonomously within DVE by activating the Wiskott-Aldrich syndrome protein family verprolin-homologous protein (WAVE) complex: specific deletion of Rac1 in VE cells phenocopies the Rac1-null embryo and that a hypomorphic mutation that disrupts the gene for Nck-associated protein 1 (Nap1; Nckap1 – Mouse Genome Informatics), a component of the WAVE complex, often results in impaired DVE migration (Rakeman and Anderson, 2006). When DVE cells reach the embryonic/extra-embryonic junction, they do not go beyond the junction but rather migrate back in the lateral-distal direction (Fig. 6). A recent study (Trichas et al., 2011) has suggested that there are regional differences in F-actin and dishevelled 2 (Dvl2) protein localization between embryonic VE and extra-embryonic VE, and that these differences may explain why DVE cells do not pass the embryonic/extra-embryonic junction.

What might be the driving force of DVE cell migration? As the involvement of Rac1 and the WAVE complex suggests, time-lapse observations (Takaoka et al., 2011) have shown that DVE migration is an active and rapid process (it takes 5 hours for a DVE cell to move from the distal tip of the embryo to the embryonic/extra-embryonic junction). The driving force may be provided by an attractant (or attractants) that is expressed at the proximal side of the egg cylinder. Indeed, dickkopf 1 (Dkk1), an antagonist of Wnt signaling, is expressed in the region immediately proximal to the DVE and is able to attract DVE migration (Kimura et al., 2000). Although the DVE still migrates normally in Dkk1 mutant embryos, a Dkk1 transgene can rescue the DVE migration defects that are present in an Otx2 (a paired-type homeobox gene) mutant mouse (Kimura-Yoshida et al., 2005), suggesting that Dkk1 is a target of the Otx2 transcription factor, which itself provides the driving force for this migration. Nodal signaling stimulates cell proliferation in pre-gastrulation embryos. Cell proliferation regulated by Nodal signaling, either in the VE (Yamamoto et al., 2004) or in the epiblast (Stuckey et al., 2011), may provide an additional driving force, although it is not clear how it would do so. Yamamoto et al. (Yamamoto et al., 2004) have reported that cell proliferation is inhibited in the AVE by Nodal antagonists, but this has not been observed by Stuckey et al. (Stuckey et al., 2011). This discrepancy may result from the differences in the methods employed to detect cell proliferation.

Finally, what determines the direction of DVE cell migration? The DVE must move from the distal tip towards the proximal side, but it could do so by taking different routes or directions with respect to the future AP polarity. Formally, one can think of two alternative scenarios. In the first scenario, the embryo is already pre-patterned with respect to its future AP polarity before the DVE starts to migrate. DVE cells thus already ‘know’ in which direction to migrate. In the second scenario, there is no pre-patterning at the time of DVE migration. As long as the DVE undergoes collective migration towards the proximal side of the embryo, it would not matter which route it takes because the side of the embryo that receives the DVE would become the future anterior side.

In reality, the expression domains of the Nodal antagonists Lefty1 and Cer1 are already shifted toward the future anterior side before the DVE starts to migrate. As described above, Lefty1 expression domains continue to localize asymmetrically, shifted towards the future anterior side, between E4.5 and E5.5 (Takaoka et al., 2006). Cer1 is expressed in the PrE at E4.75 and is more strongly expressed on one side of PrE. As the embryo grows, Cer1
expression progressively decreases, but re-appears at the distal end of the embryo between E5.25 and E5.5 (Torres-Padilla et al., 2007b). Furthermore, these proteins are able to attract DVE migration: DVE has thus been shown to migrate towards ectopic expression sites of Lefty1 or Cer1, or of both proteins (Yamamoto et al., 2004). Similarly, as mentioned above, Dkk1 can attract DVE cells (Kimura-Yoshida et al., 2005). Dkk1 expression domains change dynamically before and after DVE migration, but they may show a transient asymmetry with regard to future AP polarity. However, DVE still migrates unilaterally towards the proximal side in mutant mice that lack Lefty1 or Cer1 (or both proteins) (Perea-Gomez et al., 2002) or in those that lack Dkk1 (del Barco Barrantes et al., 2003). This lack of a migration phenotype might be due to functional redundancy between these attracting signals. Alternatively, the signals may simply confer to DVE cells a bias to the direction of their migration, with the DVE still being able to achieve collective migration towards the proximal side without such a bias.

**Functions of the DVE and AVE**

The role of the AVE in patterning the AP axis of the early embryo is well established. AVE cells located at the future anterior side of the egg cylinder secrete several signaling molecules, including Nodal inhibitors, such as Lefty1 and Cer1, as well as Wnt inhibitors, such as Dkk1. These signals act in concert on the neighboring epiblast and specify it to adopt the future head identity, whereas the region of the epiblast on the opposite side, located away from the AVE, does not receive such AVE-derived signals and adopts the future tail identity. A series of elegant manipulation experiments have thus revealed that an embryo that lacks the entire VE is not able to form head identity, whereas an AVE that is implanted into such an embryo is able to induce such an identity (Kimura et al., 2000).

What, then, is the role of the DVE? Recent studies suggest that the DVE is not required for de novo generation of the AVE but is essential for the proper migration of the newly formed AVE as a result of its initiation of the global movement of VE cells. Thus, when DVE that had been labeled with a Hhex-GFP transgene was surgically removed at E5.5, Cer1-expressing (AVE) cells were subsequently generated successfully but failed to migrate anteriorly (Miura and Mishina, 2007). Similarly, when Lefty1 (DVE) cells at E5.5 were genetically ablated, AVE cells were newly generated but were unable to migrate (Takaoka et al., 2011). In mutant mice that lack the Nodal signaling component Cripto (cryptic family 1), the AVE forms in the absence of a DVE but fails to migrate (Chu and Shen, 2010; Ding et al., 1998; Kimura et al., 2001). An examination of the behavior of the entire VE by time-lapse imaging has revealed that VE cells other than DVE and AVE cells also change their positions between E5.5 and E6.5 (Takaoka et al., 2011). Interestingly, these VE cells begin to move concomitantly

![Fig. 7. Three groups of mouse mutants that show impaired AVE formation.](image)

**A** Wild type

<table>
<thead>
<tr>
<th>Ba</th>
<th>Nodal−/− Smad2−/−</th>
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<tr>
<td>b</td>
<td>Cripto−/−</td>
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<tr>
<td>c</td>
<td>Otx2−/− Rac1−/−</td>
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**Key**

- DVE
- AVE
- Epiblast
- Visceral endoderm
- Primitive streak

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with or shortly after DVE migration, suggesting that DVE guides the migration of AVE by initiating the global movement of VE cells (Fig. 6). In support of this notion, the genetic ablation of Lefty1+ DVE cells in E5.5 embryos also impaired the global movement of VE cells (Takaoka et al., 2011).

DVE cells may have an additional role in AP patterning. Given that they express the same signals as do AVE cells, DVE cells may pattern the nearby epiblast just as the AVE does. Whether epiblast that they express the same signals as do AVE cells, DVE cells may movement of VE cells (Takaoka et al., 2011).

Reinterpretation of mouse mutants with defective AVE formation

Given that the DVE and the AVE have only recently been shown to have different origins, it is necessary to reinterpret the previously described phenotypes of mouse mutants. Thus, it is more appropriate to assess such phenotypes on the basis of four criteria: (1) whether the DVE forms; (2) whether it migrates; (3) whether the AVE forms; and (4) whether the AVE migrates (supplementary material Table S1; Fig. 7). In light of these criteria, the phenotypes of the following mutants need to be re-interpreted. In Nodal- and Smad2-null mutants, in which the VE and epiblast are not correctly specified (Brennan et al., 2001; Mesnard et al., 2006; Waldrup et al., 1998), both the DVE and AVE fail to form. The formation of the DVE (and also most probably of the AVE) is also impaired in Bmp signaling mutants, because Bmp signaling is required for the differentiation of the PrE to VE around E4.5 (Yamamoto et al., 2009). In the Cripto-null mutant, the DVE does not form at E5.5. Cerl-expressing cells (most likely AVE) do form in this mutant at E6.0–E6.5 but they fail to migrate anteriorly and remain at the distal tip of the embryo (Chu and Shen, 2010; Ding et al., 1998), indicative of a role for the DVE in guiding AVE migration. In other null mutants, such as in Otx2−/− (Perea-Gomez et al., 2001), Rac1−/− (Migeotte et al., 2010) and Prickle1−/− (Tao et al., 2009) embryos, the DVE forms at the distal tip at E5.5, but fails to migrate. Cells positive for Cerl (DVE, AVE or both) remain at the distal tip of the embryo at E6.0 and E6.5.

Conclusion

The generation of multiple lineages within the early mouse embryo and the establishment of embryonic polarity is a multistep process. Compaction, which begins at the eight-cell stage, generates the inside-outside polarity in the embryo, which in turn is responsible for the first cell fate decision that dictates whether cells will become ICM or TE. However, there may be molecular differences among blastomeres as early as the four-cell stage, and the onset of the first cell fate decision may take place earlier. The AP body axis is firmly established when the DVE migrates to the future anterior side of the egg cylinder. However, the DVE originates from a subset of cells in the late blastocyst, suggesting that the origin of AP polarity can be traced back to the peri-implantation stage. At this time, however, the origin of the first cell fate decision and that of AP polarity remain unknown, and one cannot completely exclude the presence of a maternal determinant(s) in the oocyte that plays a role in establishing AP polarity.

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Competing interests statement

The authors declare no competing financial interests.

Supplementary material

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References


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