Kidney Development and Disease in the Zebrafish

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Unraveling the molecular pathogenesis of human disease presents many experimental challenges, not the least of which is that experiments on humans are generally frowned upon. Model organisms, including the zebrafish, allow for experimental analysis of gene function and the detailed characterization of disease processes. Zebrafish have matured as a vertebrate model organism now that genetic tools for targeted “knockdowns” and unbiased mutagenesis approaches are in hand. The fish larval pronephros is a relevant kidney in which to pursue many aspects of human kidney development and disease. This short review outlines recent progress in applying the zebrafish pronephros to issues of human health and development.

Defects in Glomerulus Formation and Nephrotic Syndromes

Proper functioning of the kidney requires a structural integration of glomerular podocytes and blood vessels. In zebrafish, evidence that podocytes act to organize vessel ingrowth can be seen in (1) the expression patterns of genes that are known to play an important role in angiogenesis and (2) the recruitment of endothelial cells to clusters of podocytes in mutant embryos that lack the dorsal aorta, the normal blood supply for the pronephric glomerulus. Zebrafish pronephric podocytes express two known mediators of angiogenesis: Vascular endothelial growth factor (VEGF) and angiopoietin 2 (19,20). In a complementary manner, capillary-forming endothelial cells express flk1, a VEGF receptor and an early marker of the endothelial differentiation program (21). In normal zebrafish embryos at 40 hpf, flk-1-positive endothelial cells invade the glomerular epithelium and form the capillary loop. In floating head mutant embryos, the dorsal aorta is absent (22), and so the nascent glomeruli are deprived of their normal source of vasculature. Nonetheless, podocytes continue to express wt1 and vegf and seem to recruit flk-1-positive endothelial cells from nearby veins and go on to form a reasonably functional glomerulus (19). These results support the idea that podocytes, by expressing vegf, play a primary role in attracting and assembling the glomerular capillary tuft.

Surprisingly, zebrafish mutants that lack blood flow as a result of defects in cardiac function (23) fail to form a proper glomerular capillary tuft (Figure 2, A and B). This suggests that vascular shear force per se is required to drive capillary formation (24). Although vascular cells seem normal, they fail to express matrix metalloproteinase-2. Inhibition of matrix metalloproteinase activity by tissue inhibitor of metalloproteinase-1 injections results in a similar failure to form the glomerulus (24), indicating that degradation and remodeling of the glomerular basement membrane is a key step in capillary tuft formation.

Filtration of blood by the pronephric glomerulus can be detected by injections of fluorescence compounds into the general circulation and then monitoring the appearance of fluorescent endosomes in the apical cytoplasm of pronephric duct cells (Figure 2C) (11,19). From these data, it can be inferred that the fluorescence tracer has passed the glomerular basement membrane and entered the lumen of the pronephric tubules and ducts, where it is actively endocytosed. Using this assay, we have established that blood filtration by the zebrafish pronephros begins at approximately 40 hpf (11).

A major feature of the mammalian glomerular blood filter is the podocyte slit diaphragm, a specialized adherens junction that forms between the podocyte foot processes (25). Failure of the slit diaphragm to form results in proteinuria or leakage of high molecular weight proteins into the filtrate. Proteinuria is the cardinal feature of several human congenital nephropathies and also a common complication of diabetes (26). Several disease genes that are known to function in the slit diaphragm have been cloned. Nephrin is a transmembrane protein present in the slit diaphragm itself and is thought to contribute to the zipper-like extracellular structure between foot processes (27). Podocin is a podocyte junction-associated protein (28) that resembles stomatin proteins, which play a role in regulating mechanosensitive ion channels (29). Electron microscopy of the zebrafish pronephric glomerulus reveals that like mammalian
podocytes, zebrafish podocytes form slit diaphragms between their foot processes (Figure 2D). Zebrafish homologs of podocin and nephrin are specifically expressed in podocyte precursor cells as early as 24 hpf (Figure 2, E and F). These functional similarities between mammalian and zebrafish podocytes, coupled with assays for glomerular remodeling and morphogenesis, point to future applications of fish as a model for study and treatment of human proteinuria.

Defects in Tubules and Models of Cystic Disease

One of the most common human genetic diseases is polycystic kidney disease, which affects 1 in 1000 individuals (30). Kidney cysts are the result of grossly expanded kidney tubule lumens and, when present in sufficient size and number, lead to kidney fibrosis and end-stage renal failure. Our work has identified a relatively large set of genetic loci associated with cystic pronephroi in zebrafish (11) (Figure 3). Recently, the results of a large-scale retroviral insertional mutagenesis screen have identified 10 zebrafish genes that when mutated cause pronephric cysts (31). The requirement for a relatively large number of genes underlying maintenance of tubule structure is consistent with the idea that maintenance of lumen size and epithelial cell shape is a complex process that is controlled by many cellular proteins or signaling pathways.

A surprising convergence of findings from studies of cystic disease, left-right asymmetry, retinal degeneration, and flagella formation in the simple eukaryote Chlamydomonas have led to the idea that defects in the formation or function of cilia may underlie the pathology observed in all of these conditions. Cloning the gene that is responsible for the oakridge polycystic kidney (orpk) mouse was the first link between cilia and kidney cystic disease. The mutant gene, polaris, is a homolog of a Chlamydomonas gene, IFT88, that is required for intraflagellar...
transport, an essential process in flagellum formation (32,33). Human and mouse kidney cells are not flagellated but have a single, nonmotile apical cilium. Orpk mutant mouse kidney epithelial cells have short, malformed apical cilia (32–34), suggesting a functional link between cilia and maintenance of epithelial tubule lumen diameter. Subsequent studies revealed that most known cystic mutant genes, including polycystin 1, polycystin 2, cystin (opk mouse), polaris, inversin, and the Caenorhabditis elegans polycystin homologs lov-1 and pkd2, were, at least in part, localized to cilia (35–39). The results of a large-scale insertional mutagenesis screen in zebrafish lend further support to the link between cilia and cystic disease. Of 10 genes reported in this work, three were IFT genes associated with ciliogenesis (31). Recent studies of polycystin 1 and polycystin 2, the genes that are responsible for autosomal dominant polycystic kidney disease, indicate that they act together to mediate calcium entry into cells upon flow-induced cilium deflection (40,41). The current model of cilia function in the mammalian kidney is that the cilium acts as a sensor of tubule lumen mechanics and flow, providing a feedback signal that limits lumen diameter or cell proliferation. Our recent observations in zebrafish indicate that cilia in the pronephros are motile and have a “9 + 2” microtubule doublet organization that is typical of motile cilia and flagella (Kramer-Zucker et al., submitted). Because motile cilia are often associated with fluid flow, this leads to an alternative hypothesis that cilia may act as a fluid pump in the zebrafish pronephros. It seems that cystic kidney tubules could arise by multiple different mechanisms related to cilia function.

Several other genes that can account for tubule cyst formation have been identified in zebrafish. Nek8 is a member of the NIMA family of serine/threonine kinases and is mutated in the juvenile cystic kidney (jck) mouse (42). Disrupting the function of zebrafish Nek8 causes severe cystic distension of the pro nephric tubules. Other Nek kinases have links to cytoskeletal functions: Nek2 is localized to centrioles and acts to promote splitting of duplicated centrioles during the cell cycle (43). Further studies are needed to test whether Nek8 may have a similar role in cilia or centrosome/basal body function (44–47).

Disruption of the zebrafish homolog of the human cystic disease gene polycystin 2 also causes pronephric cyst formation (31; Obara et al., unpublished results, 2004). We have found that co-injected human polycystin 2 mRNA can rescue this phenotype, indicating that the function of polycystin 2 has been highly conserved between fish and human. This kind of result opens to the door for functional analysis of variant forms of the human PKD2 gene in an easily manipulated, in vivo model of human disease. Disruption of the zebrafish inversin gene results in kidney cysts. The human condition nephronophthisis type 2 (NPHP2) is associated with mutations in the human inversin gene (13). Both inversin and the mammalian NPHP1 gene nephrocystin are found in basal bodies and cilia and have been shown to interact biochemically. Deletion of the putative nephrocystin-binding domain in zebrafish inversin results in severe cyst formation, supporting the idea that NPHP proteins act as a multiprotein complex to regulate the function of basal bodies and/or cilia (13).

The transcription factor hepatocyte nuclear factor 1β (HNF-1β) is required for normal zebrafish pronephric tubule development (48) and, when mutated, results in glomerular cysts. HNF-1β has been shown to regulate the expression of several other cyst-associated genes in the mouse (49). Mutations in HNF-1β in humans are associated with glomerulocystic disease and maturity onset diabetes of the young, type V (50).

Conclusions

Despite some differences inorgan morphology between the mammalian and teleost kidneys, many parallels exist at the cellular and molecular levels that can be exploited to further our understanding of kidney development and disease. The same genes and cell types are used in the development and function of all vertebrate kidneys. Genes that are mutated in human disease are also essential for the formation and function of the zebrafish pronephros. The zebrafish thus presents a useful and relevant model for studies of kidney development and disease. Both gene-targeted and unbiased mutagenesis approaches to genetic manipulation in the zebrafish will no doubt continue to reveal the function of genes and cell–cell interactions that underlie the development of all kidney forms.

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