The first Blalock-Taussig shunt surgery in 1945 changed major congenital heart disease (CHD) from a universally lethal condition into a survivable one. In the 50 years that followed, rapid progress in anatomic diagnosis via echocardiography and dramatic improvement in surgical and catheterization techniques resulted in survival to adulthood and greatly improved quality of life for many individuals with CHD. Despite this, continuing progress in caring for individuals with the most complex forms of CHD is that the outcomes are highly variable, even when accounting for surgical skill and anatomic complexity. In this issue of Circulation, Nakhleh et al² show that a subset of patients with CHD and heterotaxy have airway ciliary dysfunction that may account for increased morbidity and mortality independently of the complexity of the CHD. This finding highlights a critical point that will surely affect patient care in the years to come; improving our understanding of the genetic origin of CHD is likely to affect response to therapy. The hope is that individualized therapy for CHD based on the underlying genetics will contribute to the next major improvement in outcome.

Cilia Point the Way

Martina Brueckner, MD

**Impact of Genetic Diagnosis on Clinical Management of Patients With Congenital Heart Disease**

Heterotaxy is defined as any arrangement of organs across the body’s left-right axis that differs from complete situs solitus and complete situs inversus. CHD is one of the hallmarks of heterotaxy and is characterized by a wide range of highly complex cardiac anatomy,² including but not limited to anomalous systemic and pulmonary venous return, complex atrioventricular canal, functionally single ventricle, and a range of abnormalities of the outflow tract (Table). Thus, the cardiac lesions associated with heterotaxy represent a significant surgical challenge; however, the surgical outcome in heterotaxy patients remains significantly worse than that in patients with comparably complex CHD as evaluated by the Risk Adjustment in Congenital Heart Surgery-1 score.² This indicates that a subset of patients with heterotaxy-associated CHD may have abnormalities extending beyond their heart disease that affect their response to extensive cardiac surgery. To improve outcome, we need to identify and treat the noncardiac factors in heterotaxy patients that contribute to their excessive morbidity and mortality.

Extensive evidence points to a predominantly genetic origin for human heterotaxy, and there are reports of dominant, X-linked, and recessive pedigrees affected by heterotaxy. Furthermore, the incidence of heterotaxy is increased in populations with a high degree of consanguinity, and heterotaxy is seen in association with aneuploidies and genetic syndromes, including primary ciliary dyskinesia (PCD) and Bardet-Biedl syndrome.³ Understanding the genetics of human heterotaxy is complicated by the high lethality leading to few large pedigrees and extensive phenotypic variability. At this time, mutations have been identified in 15 genes accounting for ≈10% of human heterotaxy. In contrast, the list of candidate genes for heterotaxy is much larger.⁶,⁷ If all the genes associated with human syndromic and nonsyndromic heterotaxy are listed and then genes that have been implicated in left-right development in model organisms are added, the total list of heterotaxy candidate genes currently would stand at >125 genes encompassing a broad range of biological functions (Figure). This indicates that heterotaxy is actually not a monogenic diagnosis but a manifestation of a broad range of developmental disorders that affect the development

<table>
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<th>Venous anomalies, %</th>
<th>Bilateral SVC</th>
<th>Anomalous pulmonary venous return</th>
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<td>Bilateral SVC</td>
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<td>Atrioventricular septal defect</td>
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IVC indicates inferior vena cava; SVC, superior vena cava; VA, ventricular-atrial; and DORV, double-outlet right ventricle.
of left-right asymmetry. The clinical manifestations observed in heterotaxy patients are further complicated by prominent effects on the development and function of other organ systems; for example, many of the genes affecting left-right development, through their role in cilia, also have critical effect(s) on the lung and kidney.

Almost 20% of the genes known to control left-right development have a role in the biogenesis and function of the cilium. Primary cilia are found on almost all cell types at some time, and they are central to the development of left-right asymmetry. The vertebrate left-right axis is initiated at the mammalian left-right organizer late in gastrulation when motile primary cilia found on left-right organizer cells generate directional flow of extraembryonic fluid called nodal flow. The direction of nodal flow is determined by the inherent chirality of the cilium itself. Sensory cilia transduce nodal flow into asymmetrical gene expression, which is then interpreted by the developing heart to direct asymmetrical cardiac morphogenesis. Cilia, however, have a host of other functions during embryogenesis; they are essential for the development and function of the kidney, bones, and brain. They are found on the cells of the developing myocardium and after birth, motile cilia in the respiratory tract are required for effective clearance of secretions. Seminal work by Afzelius showed that patients with PCD have structural ciliary defects as the cause of their sinopulmonary disease. Notably, 6.5% of patients with a primary diagnosis of PCD also have heterotaxy. Because patients with heterotaxy have a higher incidence of perioperative respiratory complications than nonheterotaxy patients undergoing equally complex cardiac surgery, the question addressed in the article by Nakhleh et al is whether a subset of heterotaxy patients have previously undiagnosed ciliary defects predisposing them to respiratory complications. The authors use a combination of physiological measurements of ciliary function, including direct imaging of cilia obtained from a nasal biopsy, and nasal nitric oxide measurements to assess patients for ciliary dysfunction. These techniques are more sensitive than the standard transmission electron microscopy approach more commonly used to diagnose PCD. Notably, 42% of heterotaxy patients had ciliary dysfunction compared with unaffected control subjects. Thus, during very early embryonic development, a subset of patients with heterotaxy have abnormal left-right and cardiac development as a result of abnormal ciliary function. Because cilia are required in the airway throughout life, these patients also have chronic pulmonary disease that is a variant of PCD. The perioperative respiratory complications in at least some heterotaxy patients are thus likely not caused exclusively by their cardiac surgery but may be the product of intrinsic pulmonary abnormalities coupled with the stress of cardiopulmonary bypass and assisted ventilation.

With the advent of high-throughput sequencing, we will be able to define the precise genetic abnormality(s) underlying a significant amount of CHD. The obvious question this raises is, Can we diagnose it, but can we treat it? In the case of the heterotaxy patients who have ciliary abnormalities, there are promising approaches to improve their care. PCD without associated heart disease frequently presents with neonatal respiratory distress manifested by unexplained recurrent atelectasis, poor feeding, and failure to thrive. These symptoms resemble those associated with many types of CHD, complicating and delaying the diagnosis of intrinsic pulmonary disease. Even without associated CHD, PCD leads to chronic bronchitis, recurrent pneumonia, and eventually bronchiectasis in a subset of patients. The progression of PCD-associated respiratory disease can be significantly slowed by proper therapy, and currently the lifespan of PCD patients without CHD is approaching normal. In the cardiac patient population, the pulmonary manifestations of PCD are very likely exacerbated by CHD itself and by some of the interventions required in the care of patients with complex CHD. For example, because PCD patients are entirely dependent on cough for airway clearance, intubation and mechanical ventilation, which are a necessary evil in CHD surgery, are particularly challenging. Careful perioperative management of secretions and minimizing assisted ventilation may improve immediate perioperative care. It may be beneficial for CHD-PCD patients to have intensive regular chest physiotherapy, even while they appear clinically well. There is some evidence that β-agonists increase ciliary beat frequency and therefore may be beneficial in those CHD-PCD patients with slowed ciliary beat. Finally, in contrast to care of CHD, aggressive antibiotic management of pulmonary symptoms is a cornerstone of PCD care.

It is highly likely that patients with anatomically similar, but genetically distinct, cardiac lesions will benefit from individualized care tailored in no small part by their genetic diagnosis. An atrioventricular canal defect resulting from trisomy 21 is a different disease from that arising from a defect in cilia and the development of left-right asymmetry. We need to evaluate whether therapies aimed at specific genetic diagnoses are beneficial to CHD patients. This will require large, multicenter studies combining CHD genomics with clinical research evaluating the benefit of focused clinical management strategies. The work presented in this issue of Circulation linking ciliary defects and the vexing CHD seen in heterotaxy is a first step in this direction.
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Disclosures
None.

References

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